Institute of Modern Physics

Budker Institute of Nuclear Physics

Experiences with Polarized Atomic Beam Sources and Spin Physics at BINP

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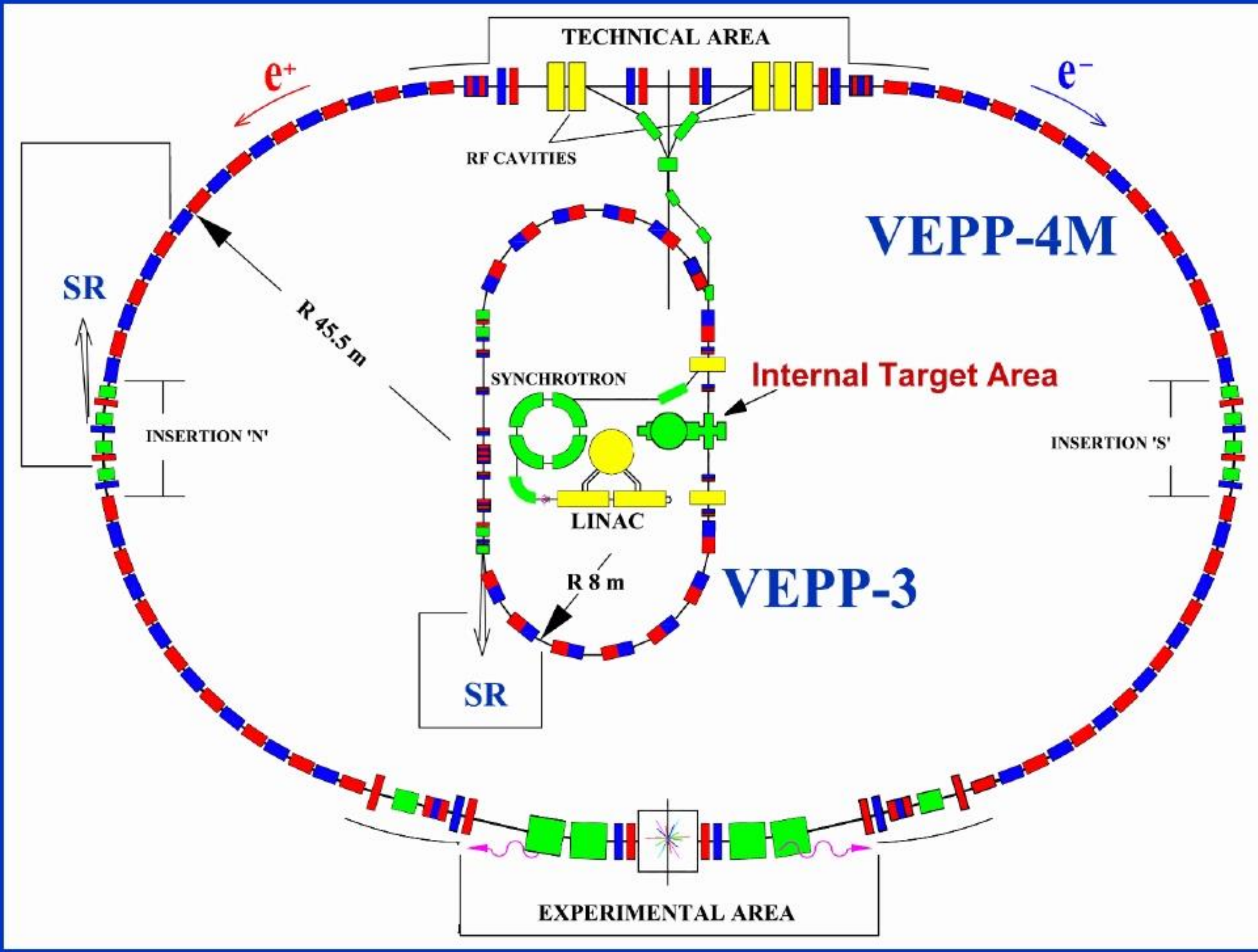
- Conclusion

Novosibirsk electron-positron facility

Experiments with POLARIZED deuteron target and UNPOLARIZED hydrogen target were conducted from mid of 80 years of last centure.

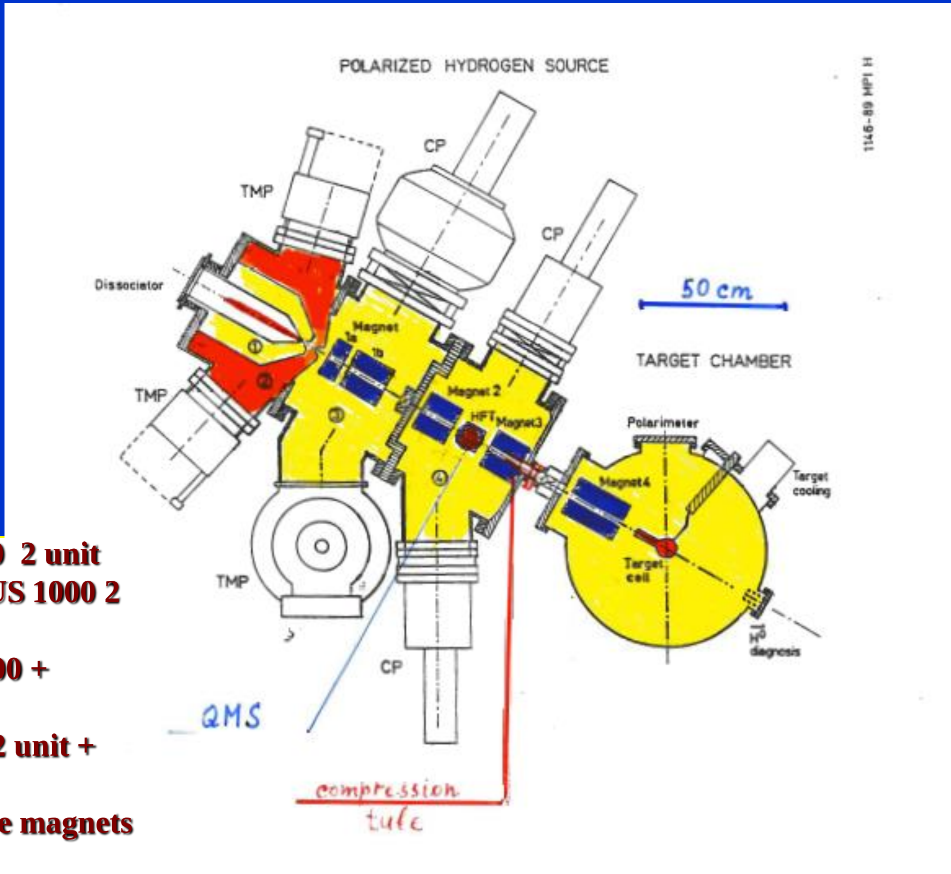
Some pioneer experiments have been performed at VEPP-3



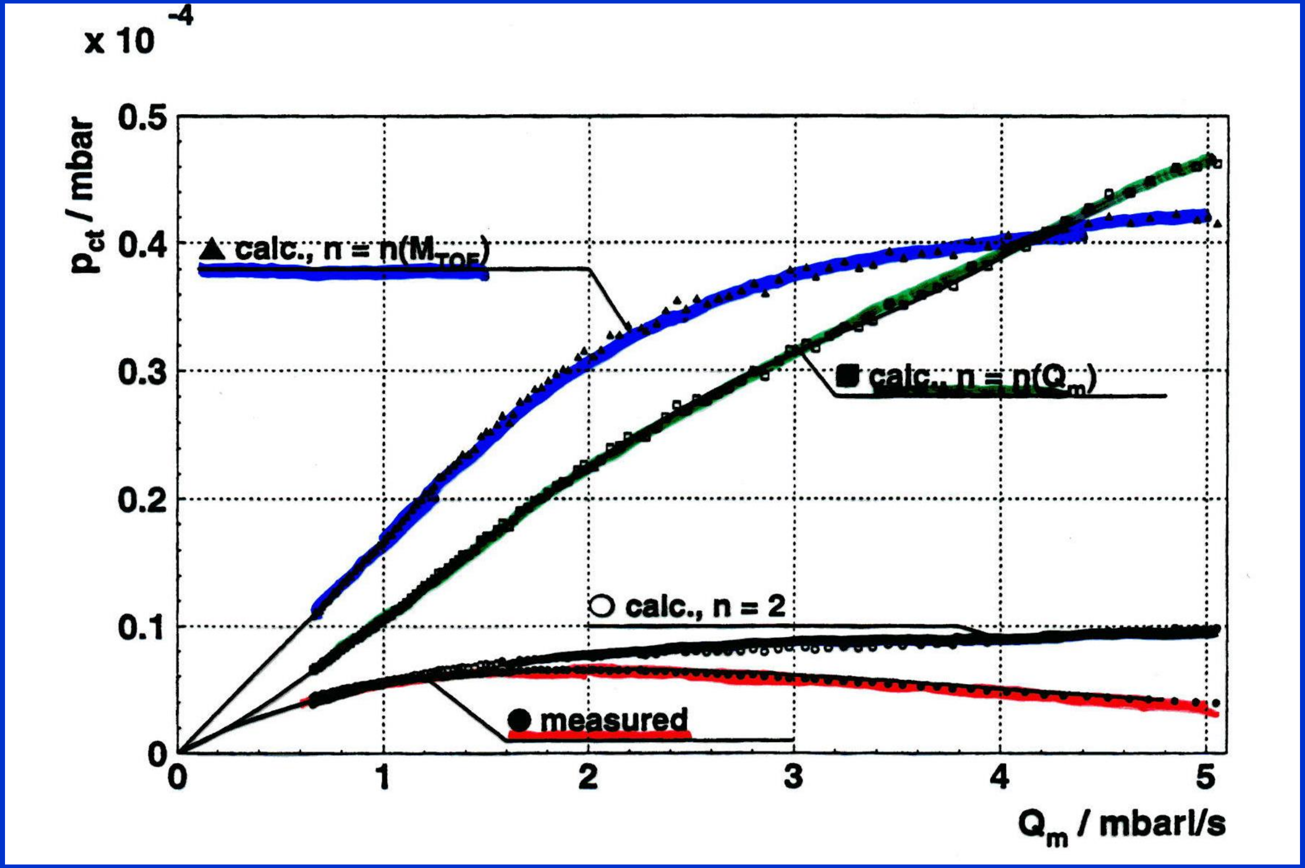
VEPP-3

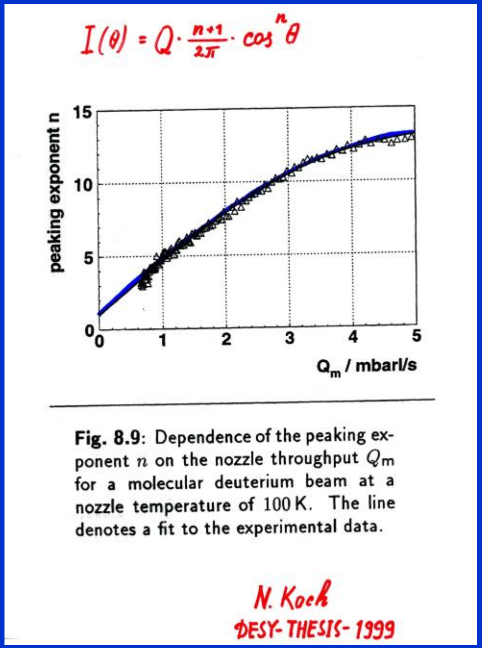
Energy : 2000 MeV
Lifetime : 20000 s
Av. current : 100 mA
Bunch : 0.7x0.3 mm

Formation of the atomic or molecular beam



BALZER TMP 2200 2 unit
LEYBOLD-HERAUS 1000 2 unit.
BALZERS TMP 2200 + KRYOPUMP 3500
KRYOPUMP 1500 2 unit + TMP 360
Permanent sextupole magnets
B = 1.5T

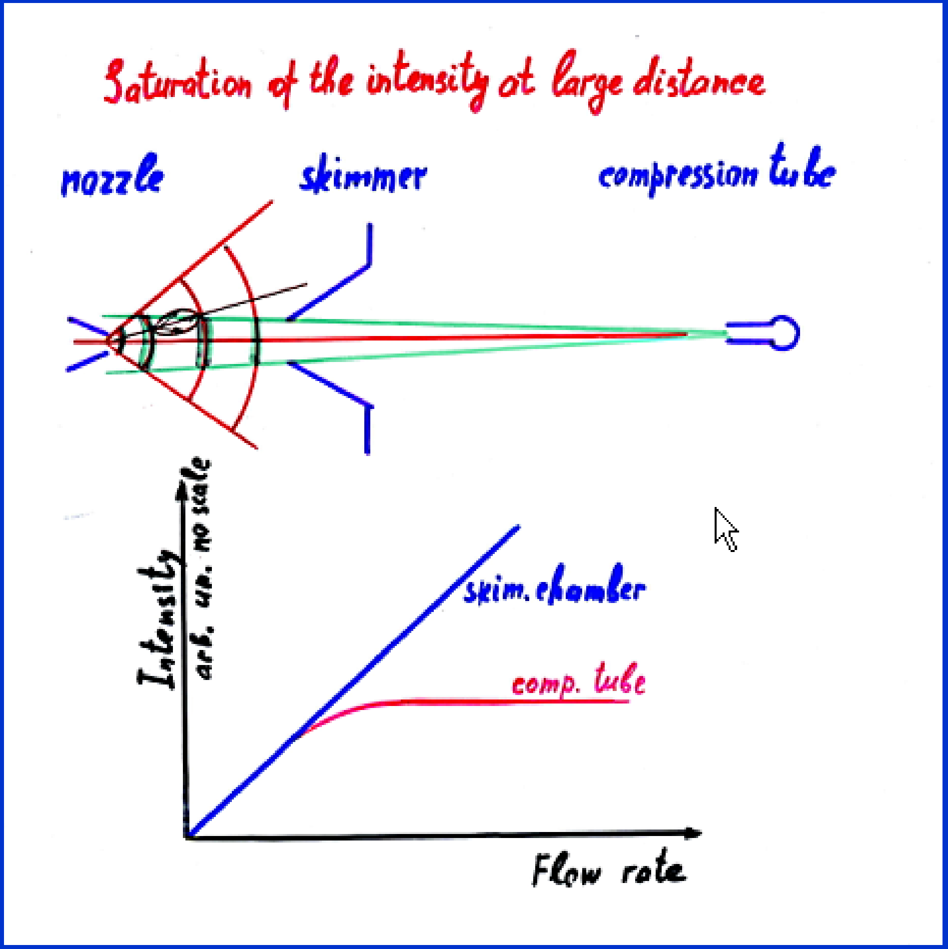




Peaking factor - increasing directivity

Dependence of the pressure rise in the compression tube on the nozzle throughput for a molecular deuterium beam at a nozzle temperature 100 K. Shown are the measured values (full dots), and those calculated for various peaking exponent. [N. Koch. A study on the Production of the Intense Cold Atomic Beams for Polarized Hydrogen and Deuterium Targets. DESY-THESIS-1999-015, 1999.]

Two effect which may to provide limitation of the intensity



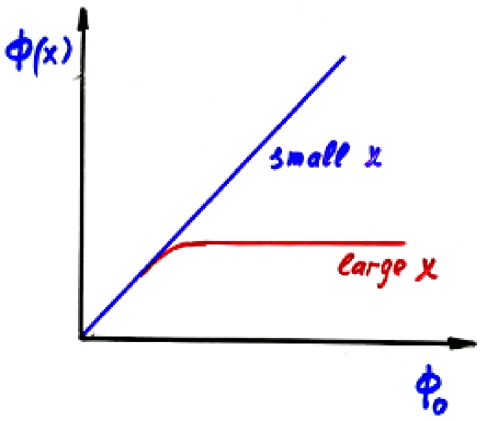
INTRA BEAM SCATTERING

Zankel K. 1972 J.Phys. B: Atom.Molec.phys. 5,74-9.

$$d\Phi = -\alpha\Phi^2 dx$$

$$\alpha \approx \frac{\Delta v \cdot \sigma}{v_{max}^2}$$

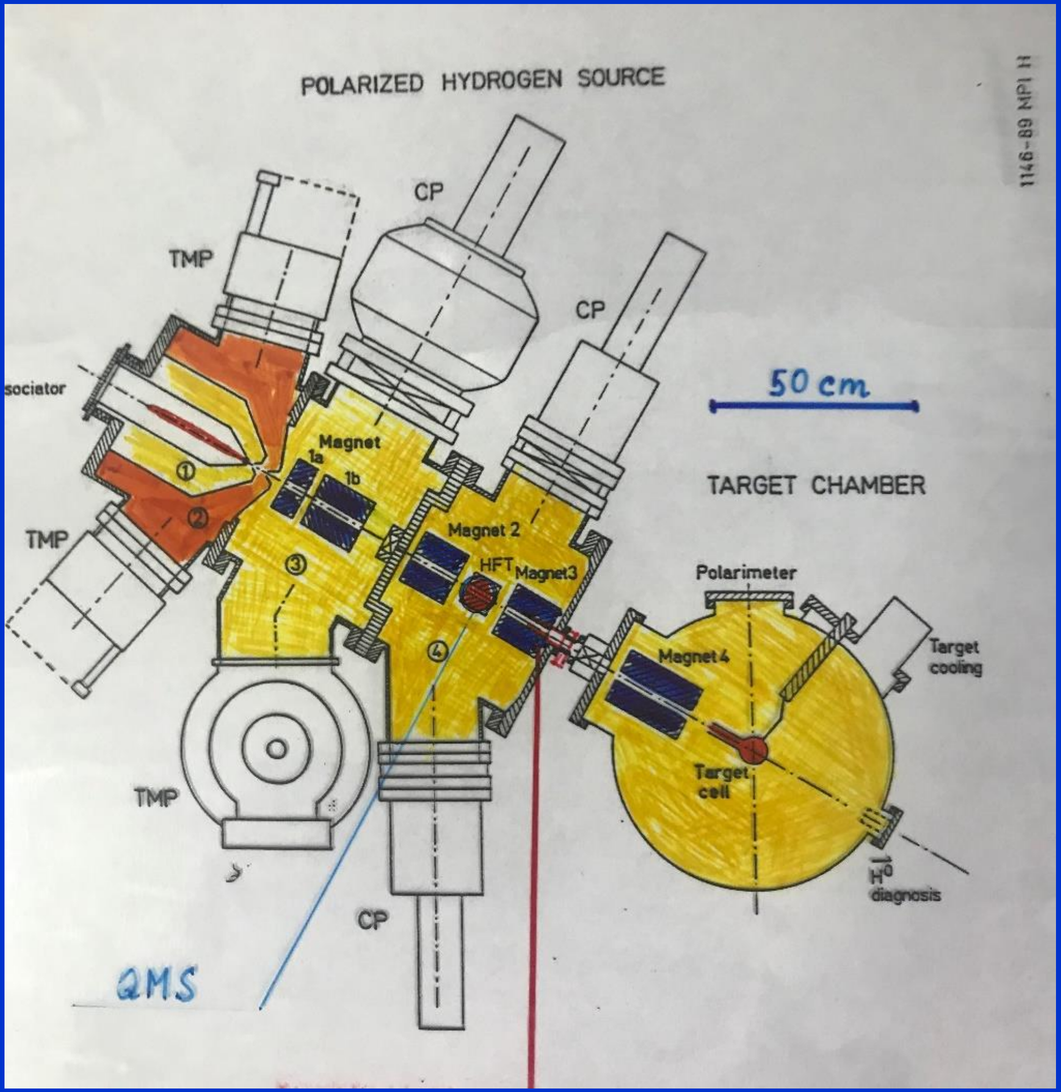
$$\Phi(x) = \frac{\Phi_0}{1 + \alpha \cdot \Phi_0 \cdot x}$$



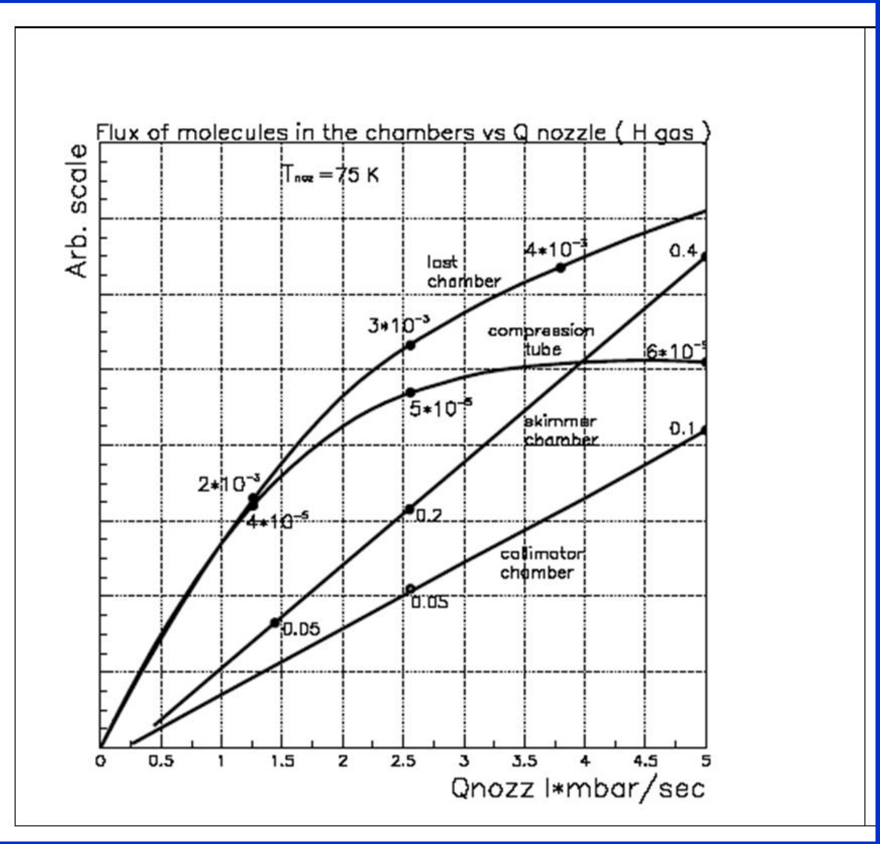
Shielding by the skimmer

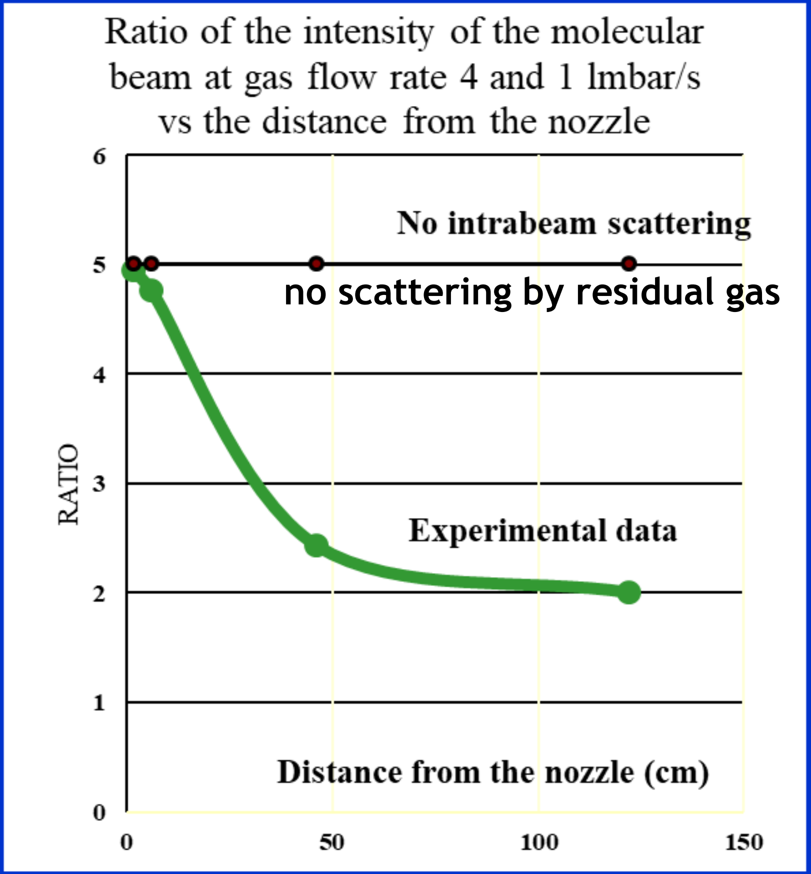
Schema of the TSR Atomic Beam Source

Measurements have been performed with molecular hydrogen beam. All magnets were removed from the source.
Each chamber of the source may be treated as a detector of the intensity of the beam. So it is a way to measure intensity of the beam at different distance, just writing the data from vacuum sensors.



Intensity measurement of a molecular hydrogen beam at HERMES source in 1991.



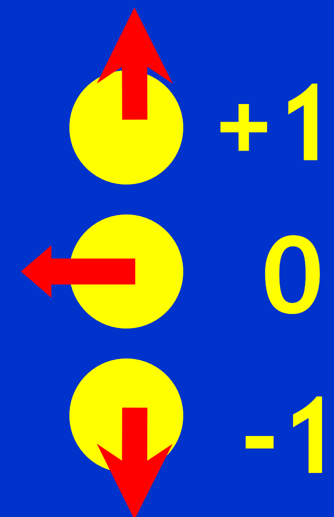


Experimental data shows strong evidence that intrabeam scattering restricted the intensity of the beam

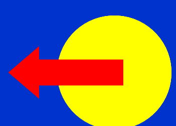
Polarization of sample of spin 1 particles

$$P_z = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_0 + N_\downarrow} = n_\uparrow - n_\downarrow$$

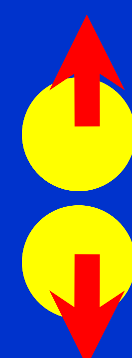
$$P_{zz} = \frac{N_\uparrow + N_\downarrow - 2N_0}{N_\uparrow + N_0 + N_\downarrow} = 1 - 3n_0$$



Tensor polarized target allows to measure tensor-polarization observables in e-d scattering even with electron beam is not polarized

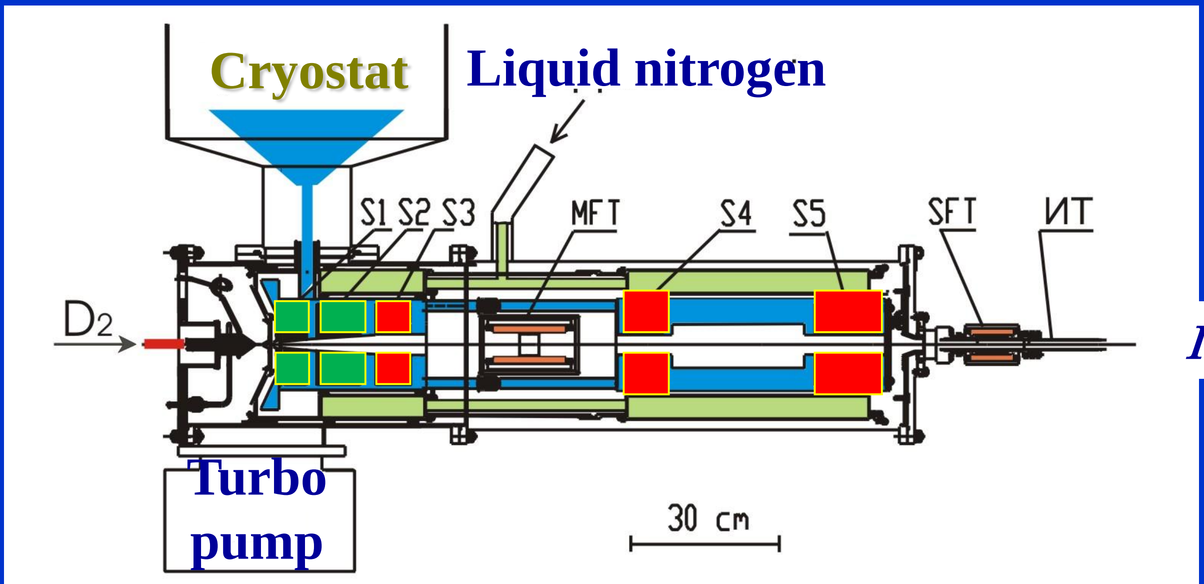


P_{zz}=-2

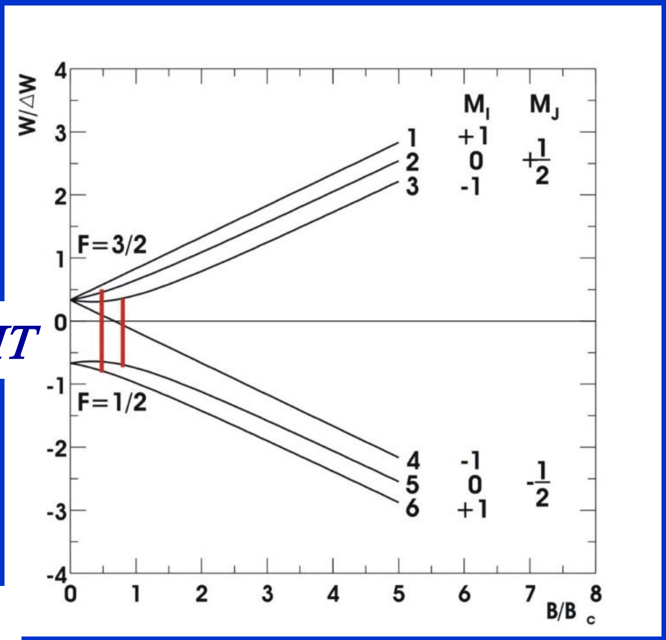


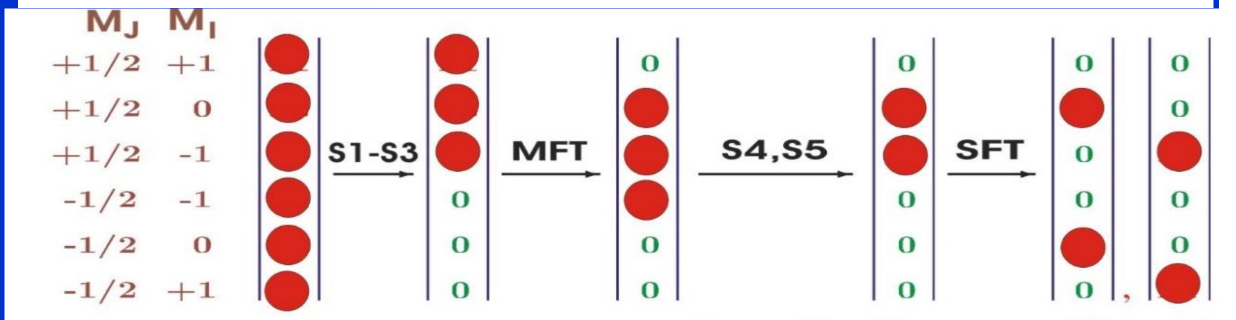
P_{zz}=1

Cryogenic Source of Polarized Atomic Beam



IT





Tensor polarization $P_{zz}=1-3n_0= -2,+1.$

Vector polarization $P_z=n_+-n_- = 0.$

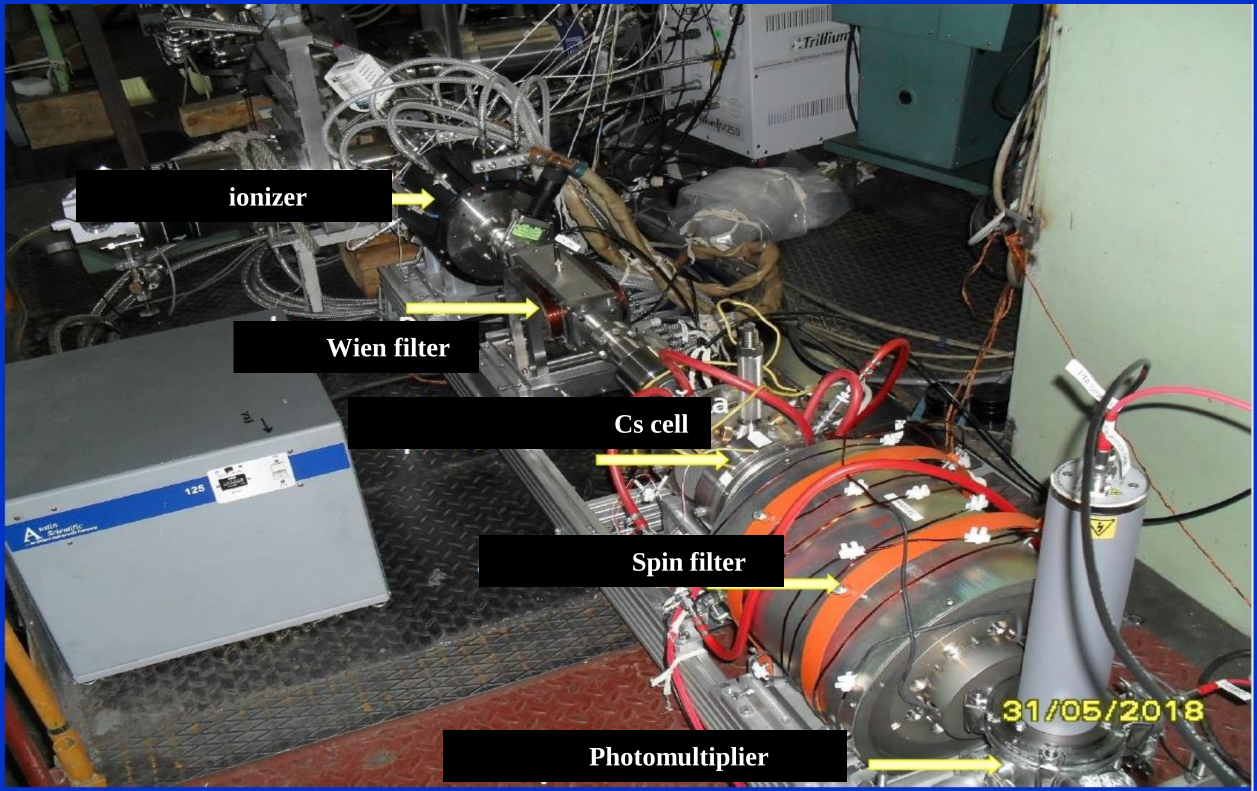
M.V.Dyug et al., Nucl. Instrum. Methods, 495 (2002) 8.

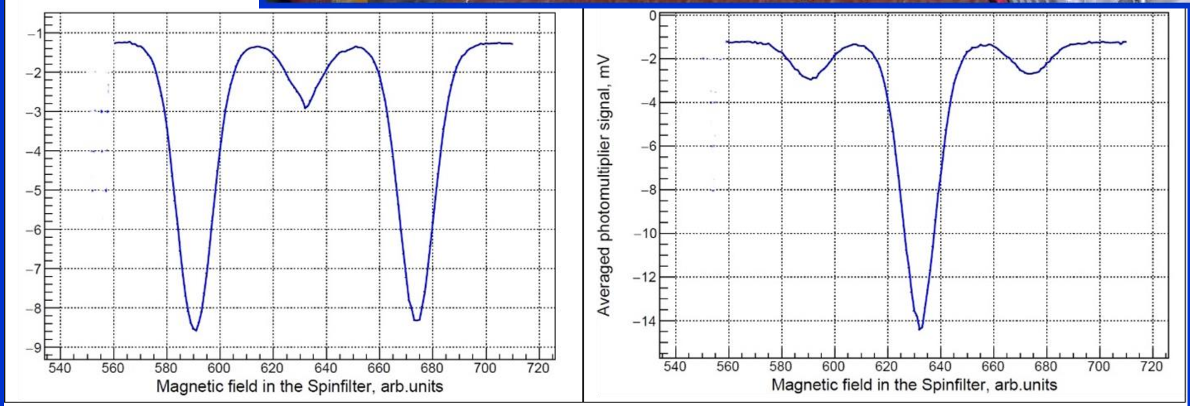
Superconducting magnets

L.G. Isaeva et al.,NIM A411(1998)201

Current, Am	Magnetic field, kGs 1-st magnet	Magnetic field, kGs 2-nd magnet	Magnetic field, kGs other magnets
10	3.25 – 3.75	4.1 – 4.5	2.2
20	6.5 – 7.5	8.1 – 9.0	4.5
30	9.2 – 10.8	10.8 – 12.0	7.0
50	12 .0 – 14.0	15.3 – 17.0	11.0
100	15.6 – 18.4	20.7 – 23.0	16.0
150	19.3 – 22.7	24.3 – 27.0	20.0
200	23.0 – 27.0	30.0 – 34.0	24.0
220	-	-	25.5
250	-	-	28.0
300	-	-	31.0
350	-	-	35.0

Lamb Shift polarimeter



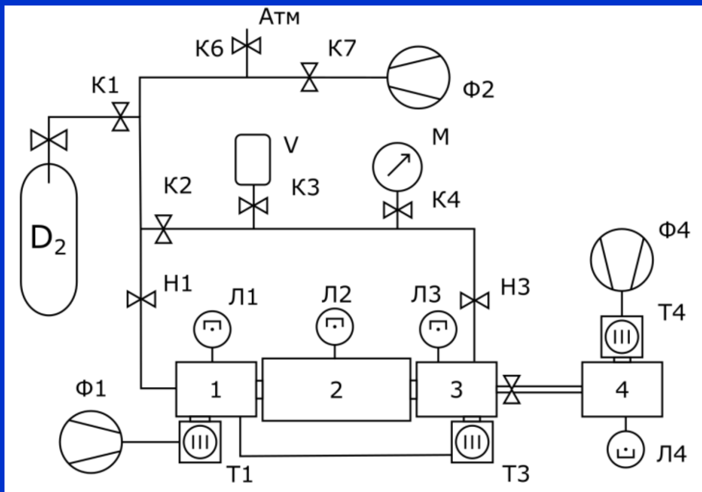


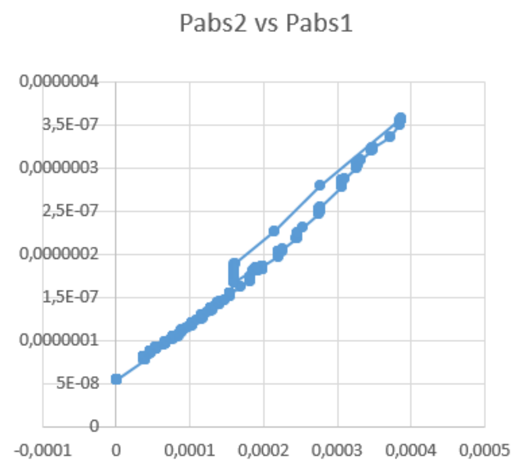
Pzz = 0.91+-0.03

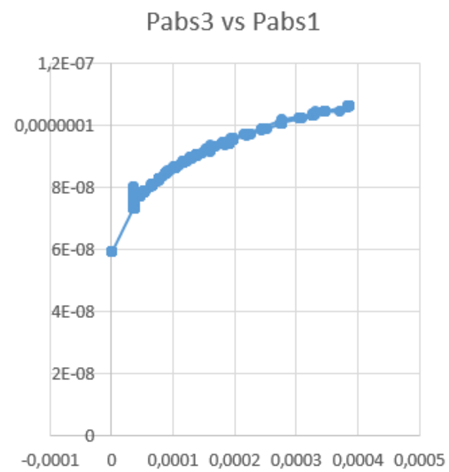
Pzz = -1.77+-0.03

Pribori I Technika Experimenta
2023, № 4, c. 13-20
In Russian.

Intensity of the focused deuterium beam Measurements have been performed in 2025

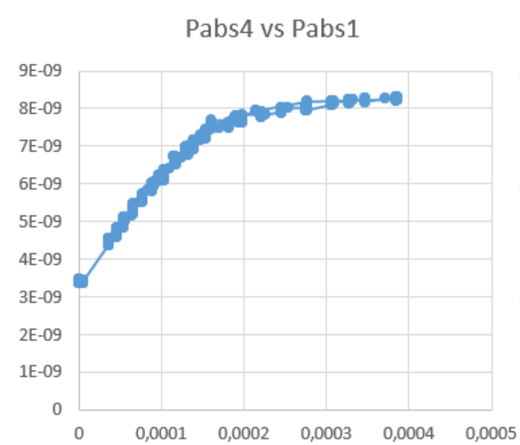






Schema of test stand

Readings of every vacuum sensor and current through the magnets were written to database every 2 seconds.



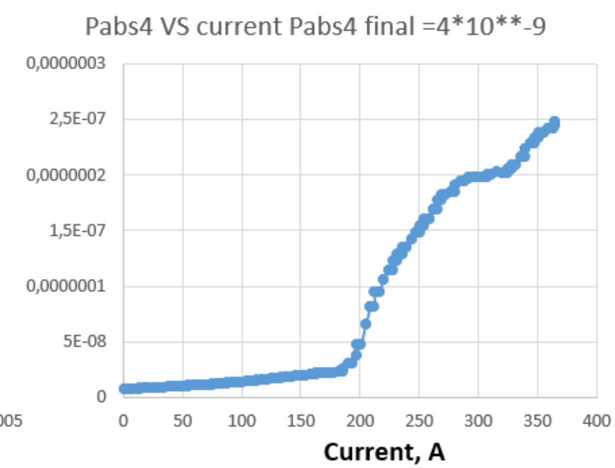
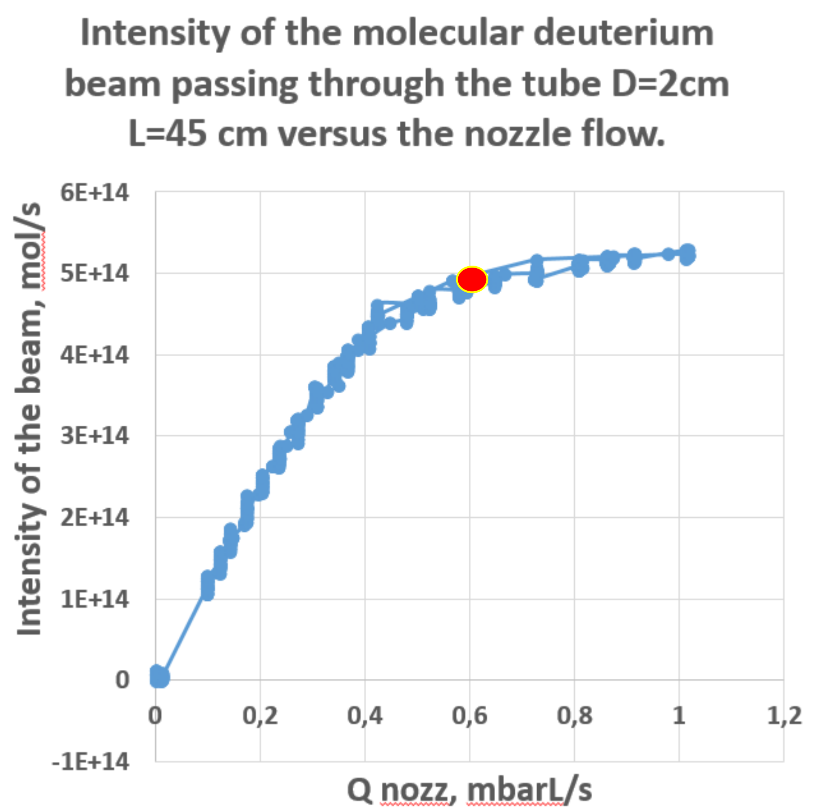
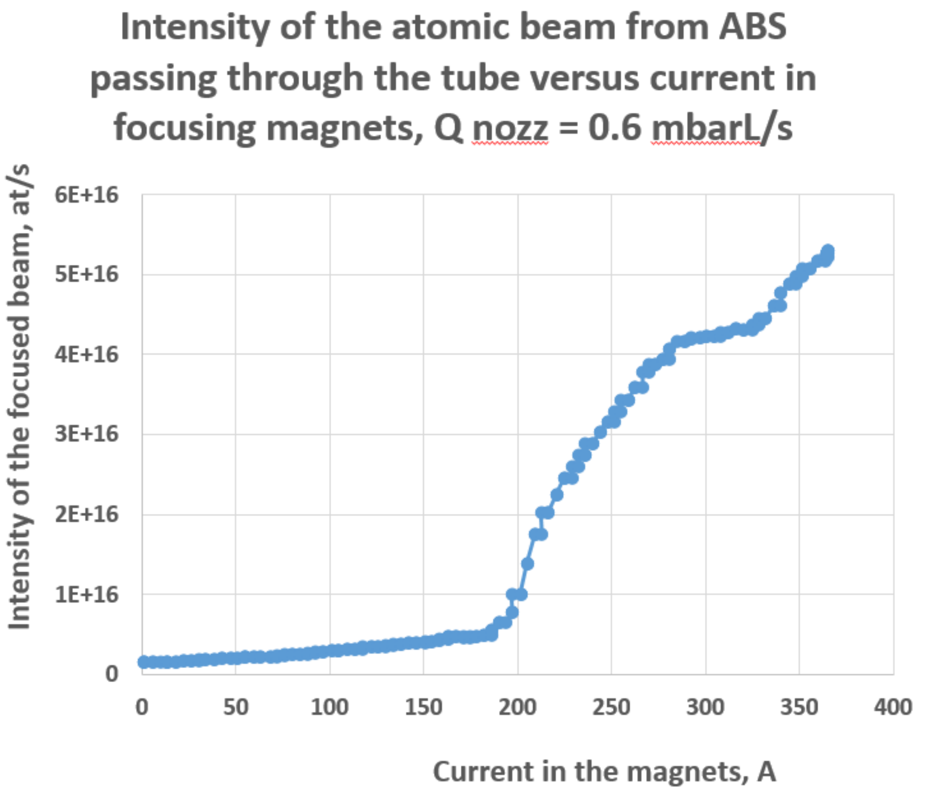


Photo of the part of test stand

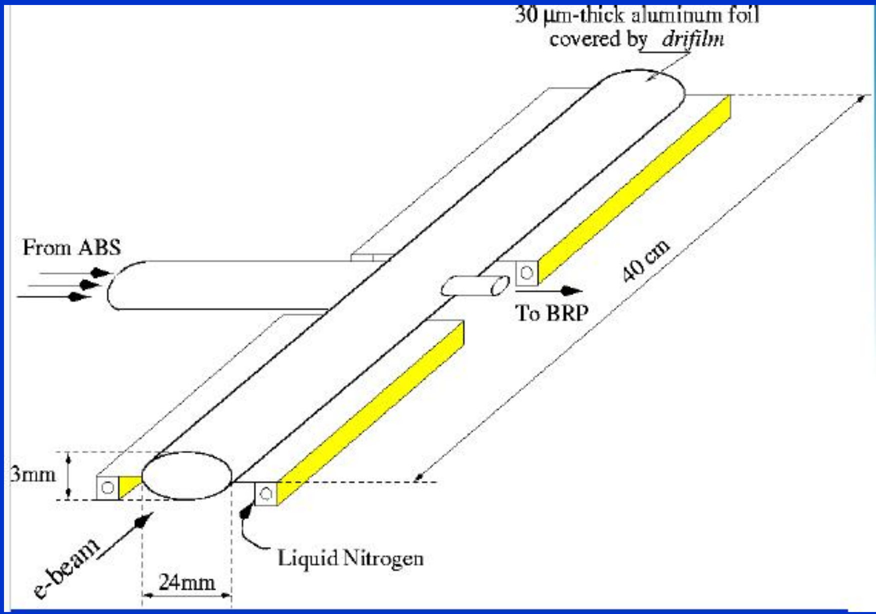
Focusing property of Cryogenic ABS





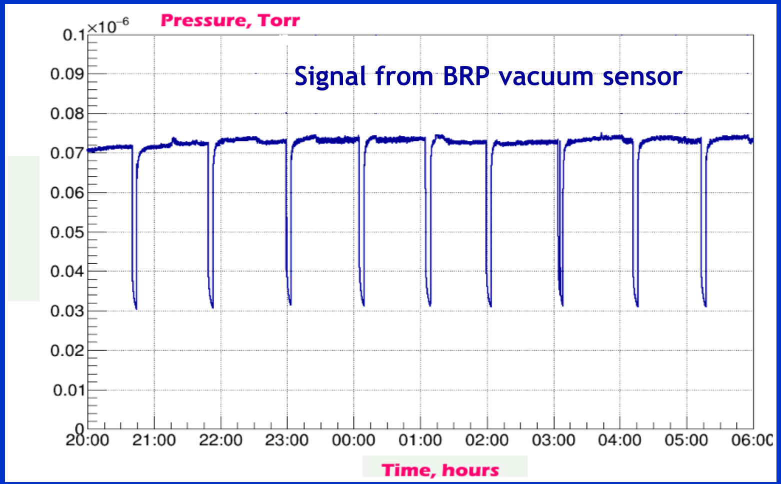
Factor of focusing ~ 100 measured, ray tracking calculation - 127
Amount of unpolarized molecules D_2 less then 1%

Storage cell for polarized atoms



Atoms, injected into the cell, reflecting from its surface may cross the circulated in the ring beam many times resulting in the increase of the target thickness by two orders of magnitude (depending on the geometry of the cell) in comparison with the jet target.

Depolarization of atoms inside the cell

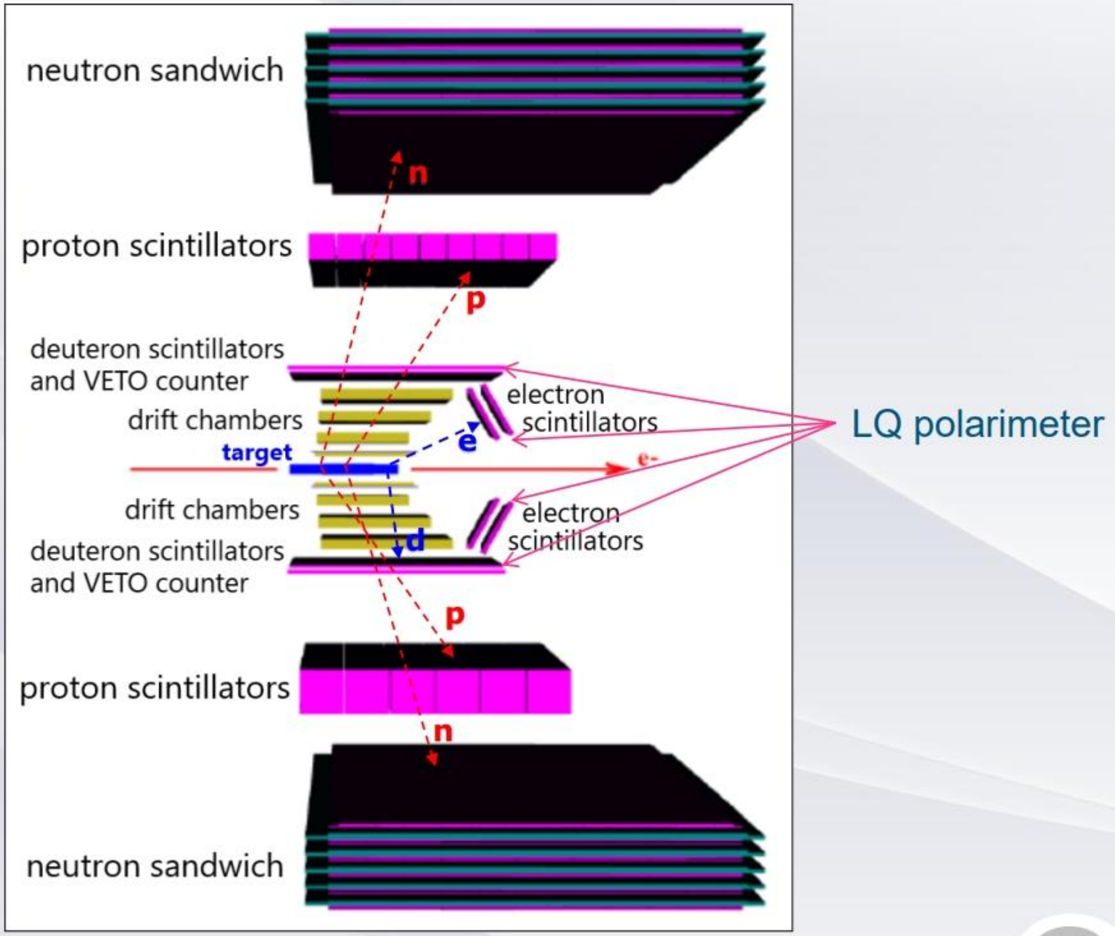


Target polarization measurement - elastic ed scattering at low momentum transfer

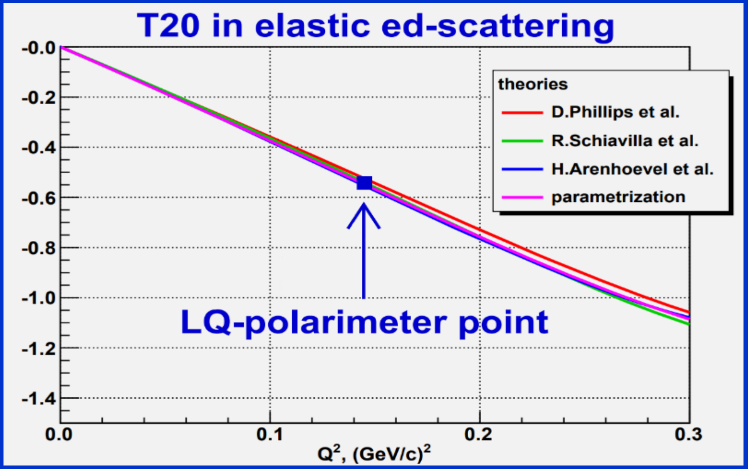
The detector system consists of two symmetrical arms for detecting proton and neutron in coincidence.

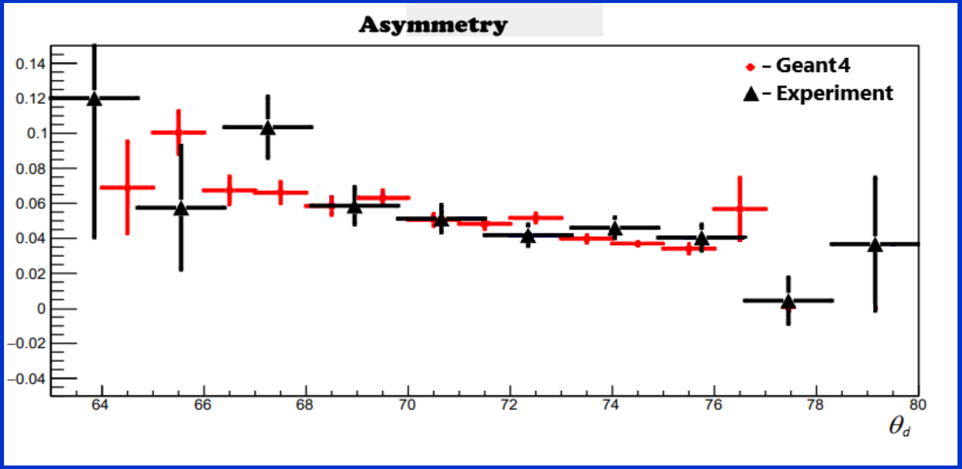
The tensor polarization of the target is measured using a LQ polarimeter.

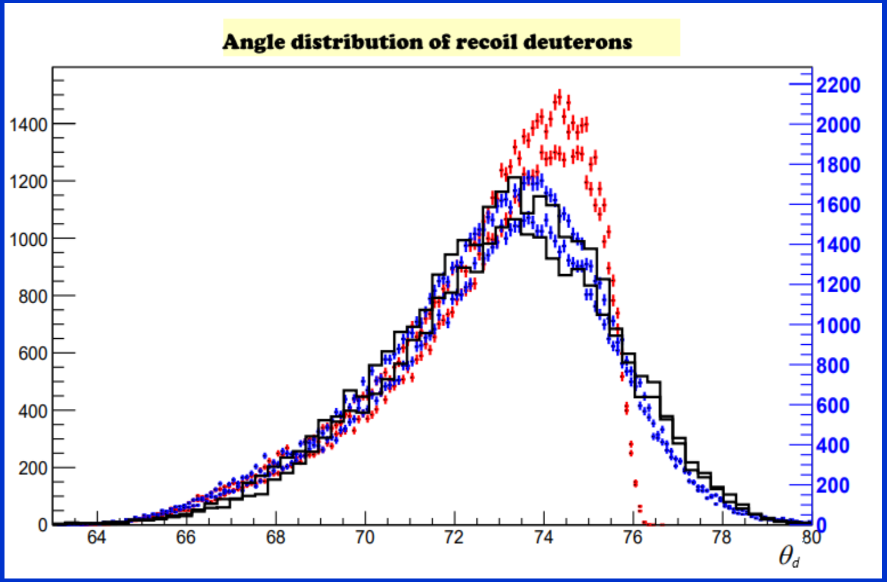
It consists of two symmetrically located sets of scintillation counters for detecting electron and deuteron in the process of elastic e-d scattering.



The results of target tensor polarization measurement



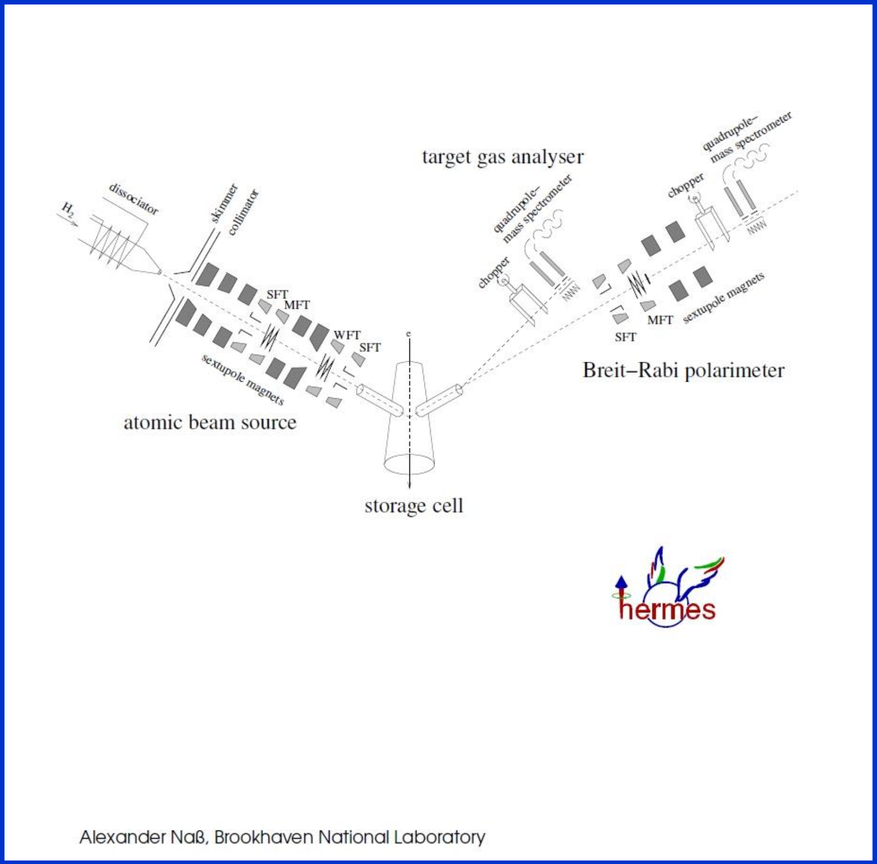


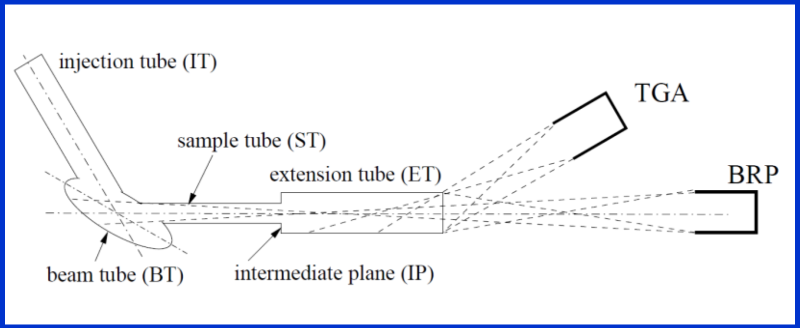


The tensor polarization is a free parameter in the simulation and shosen so that the calculated asymmetry coincides with the experimentally measured one.

Pzz = 0.39 +- 0.03 for one state and
Pzz = -0.66 +- 0.06 for the other

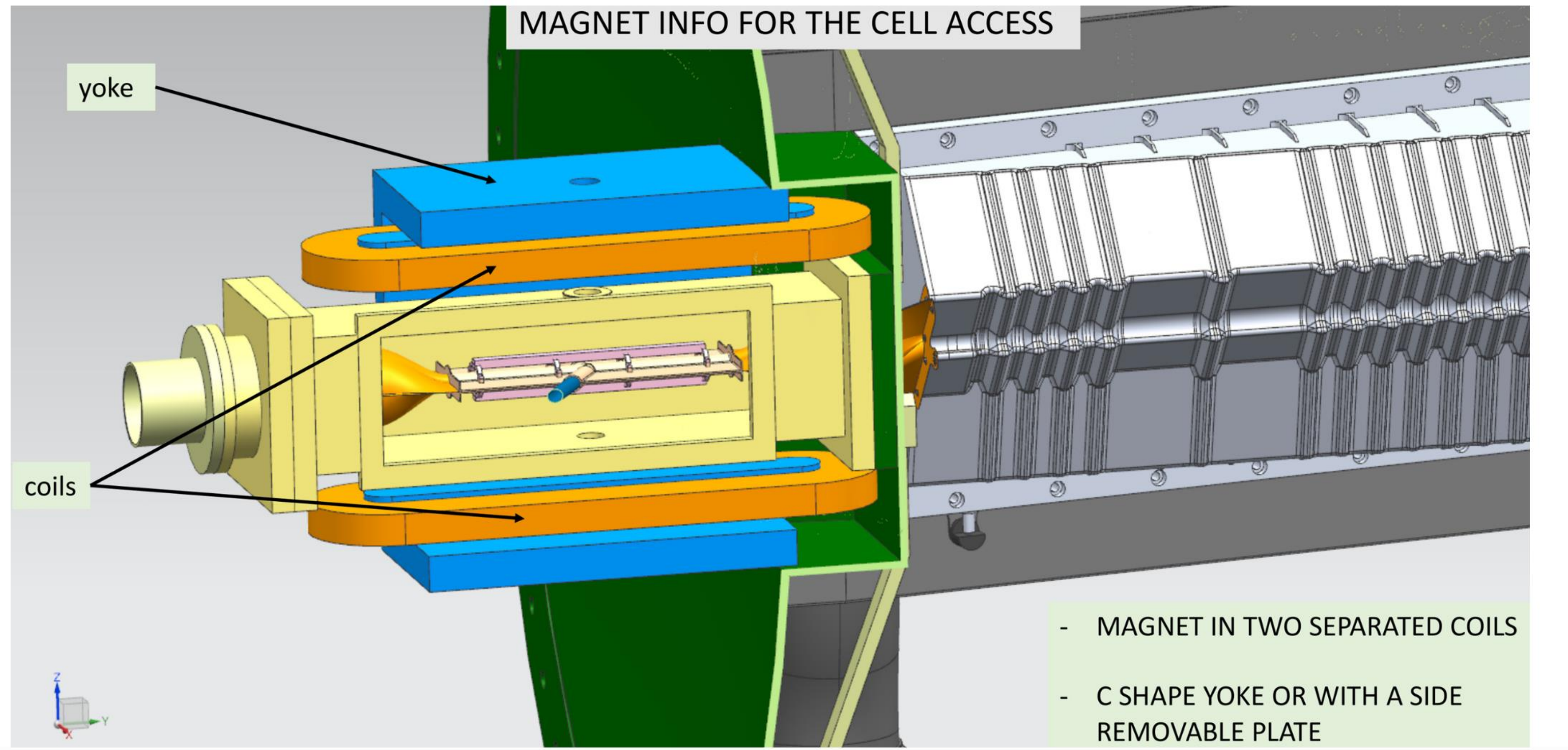
Measuring average target polarization at HERMES experiment





Studies of Spin Relaxation and Recombination at the HERMES Hydrogen/Deuterium GasTarget Dissertation of *Christian Baumgarten*, Munchen, 31, May 2000

Storage cell for polarized molecules at LHC



arXiv:2504.16034v1 [hep-ex] 22 Apr 2025

Breit Rabi polarimeter can not measure the polarization

Polarimeter based on Coulomb-Nuclear Interference (CNI)

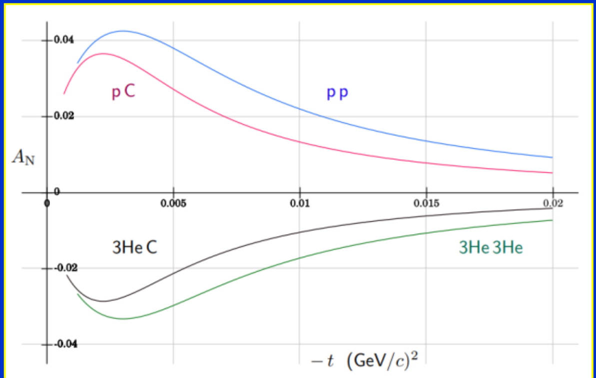


Figure 3: Analyzing power A_N versus invariant momentum transfer (-t) in (GeV/c)^2 for (1) p p and p h scattering, (2) p C scattering, (3) h C scattering, (4) h h and h p scattering

Nigel Buttimore

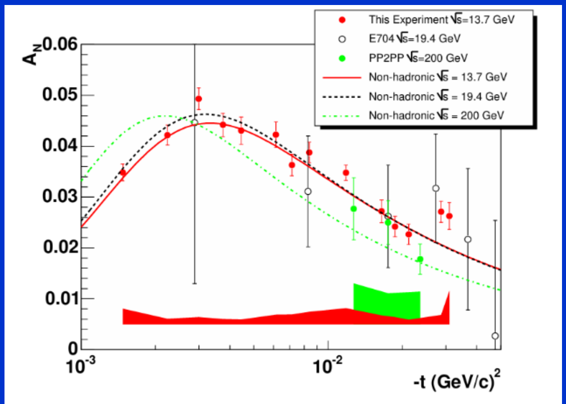
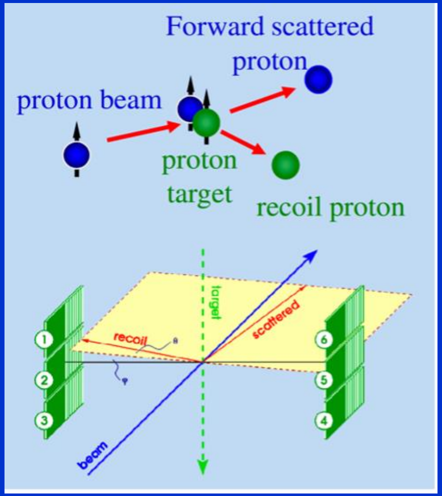


Figure 5.5: A_N as a function of t for $pp \to pp$. The results of this experiment which are measured at $\sqrt{s} = 13.7$ GeV are indicated by the filled-red circles. The empty circles are measured at $\sqrt{s} = 19.4$ GeV by the E704 experiment at FNAL. The filled-green circles are measured at $\sqrt{s} = 200$ GeV by the PP2PP experiment at BNL. The errors on the data points are statistical. The red solid, black dashed and green dotted-dashed lines are the functions without allowing for a hadronic spin-flip contribution to A_N for these $\sqrt{s}$, respectively.



$P_{beam} = \frac{\varepsilon_{beam}}{A_N}$ - beam polarization,

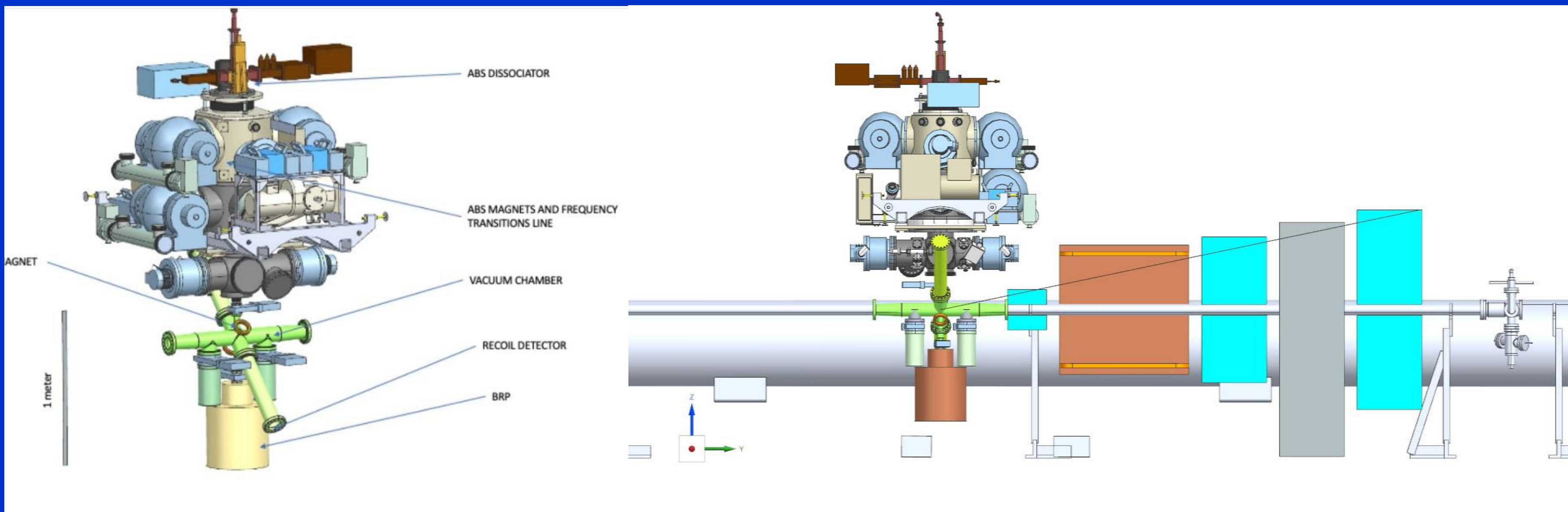
$A_N = -\frac{\varepsilon_{target}}{P_{target}} = \frac{\varepsilon_{beam}}{P_{beam}}$ – analizing power of the polarimetric reaction

$P_{beam} = -P_{target}\frac{\varepsilon_{beam}}{\varepsilon_{target}}$

$$\varepsilon = \frac{\sqrt{N_\uparrow^L * N_\downarrow^R} - \sqrt{N_\uparrow^R * N_\downarrow^L}}{\sqrt{N_\uparrow^L * N_\downarrow^R} + \sqrt{N_\uparrow^R * N_\downarrow^L}}$$

An experimental setup at the IR4

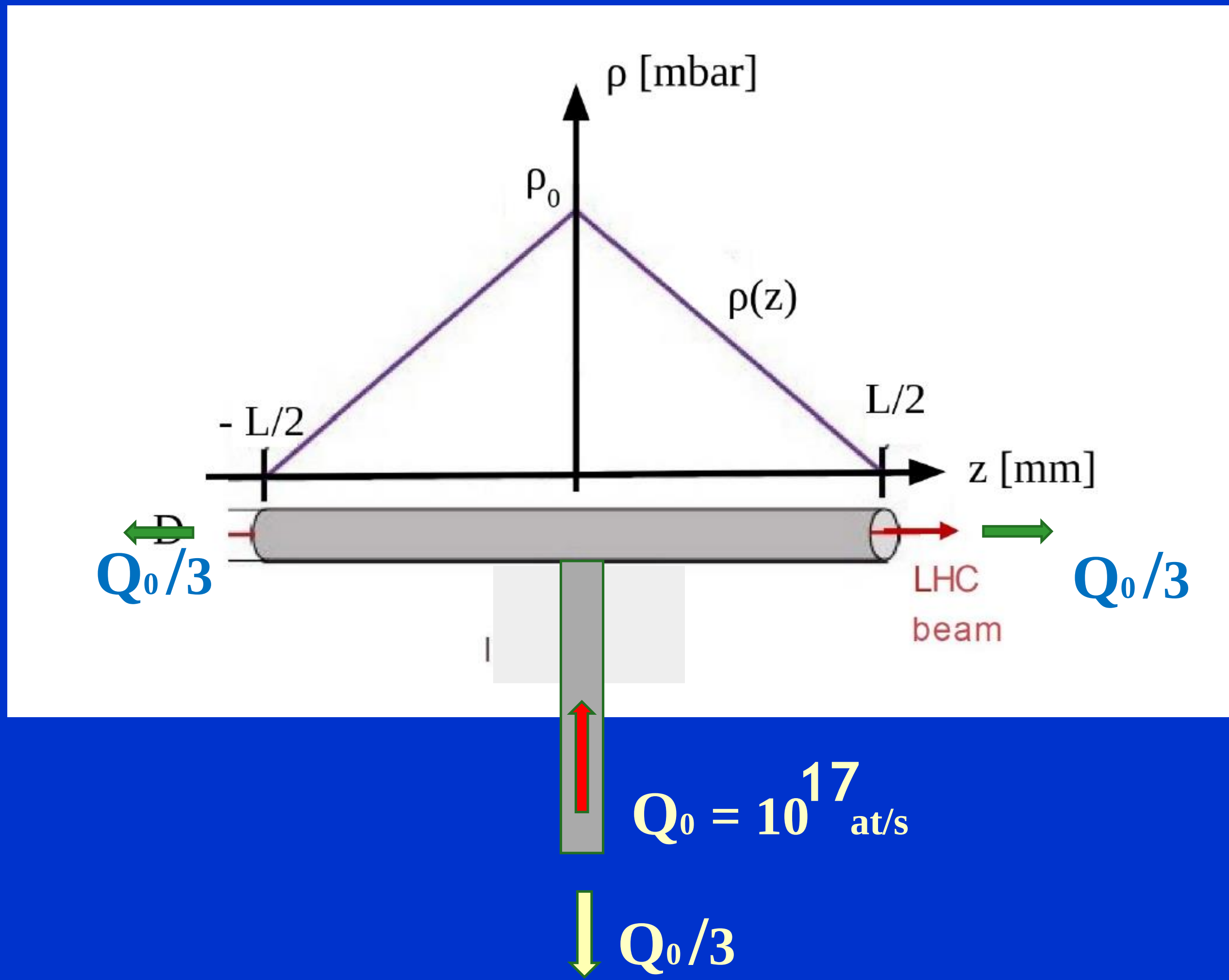
arXiv:2504.16034v1 [hep-ex] 22 Apr 2025



From left to right: the polarized gas target, a first tracking detector, a dipole magnet, the second tracking detector, an absorber wall, and a muon detector.

Spin asymmetry A_N will be determined for given beam energy with the use of polarized jet target from ABS with known polarization

Storage cell for atoms in the ring

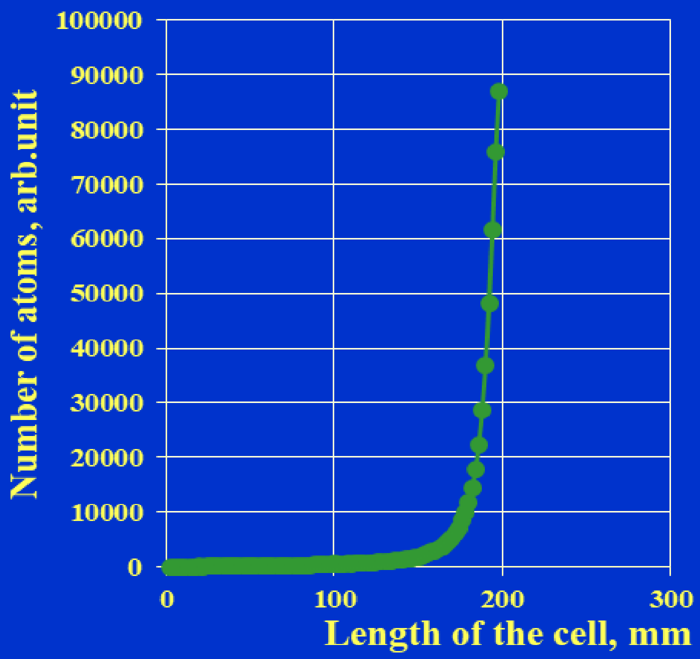


Parameters of the storage cell and atomic beam from ABS

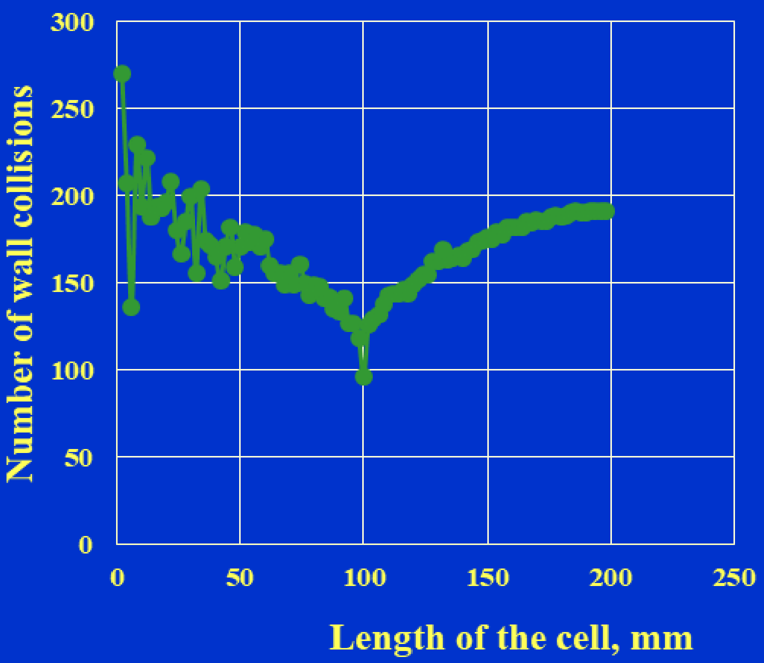
- Injected beam – diameter 1 cm, uniform density around the radius, the flux of the injected beam Qinj = **1.*10**17 at/s** =n0***V***s**t**
- **v =10**5cm/s**
- **n0** = Qinj **/St** /v== **1.2*10**12 at/cm**3**
- Target thickness of the injected beam n0 *1cm = **1.2*10**12 at/cm2 = t0**
- Assume that the velocity of atoms leaving the cell is the same **v**
- All shoulders of the cell have diameters **1 cm** and equal length = **10 cm**, it means that they have equals vacuum conductance
- For such geometry of the cell injected atoms will leave the cell through three shoulders in equal amount

Distribution of number of atoms along the cell which leave the cell from one of its ends

Distribution of atoms leaving the cell from one of its end VS the length of cell

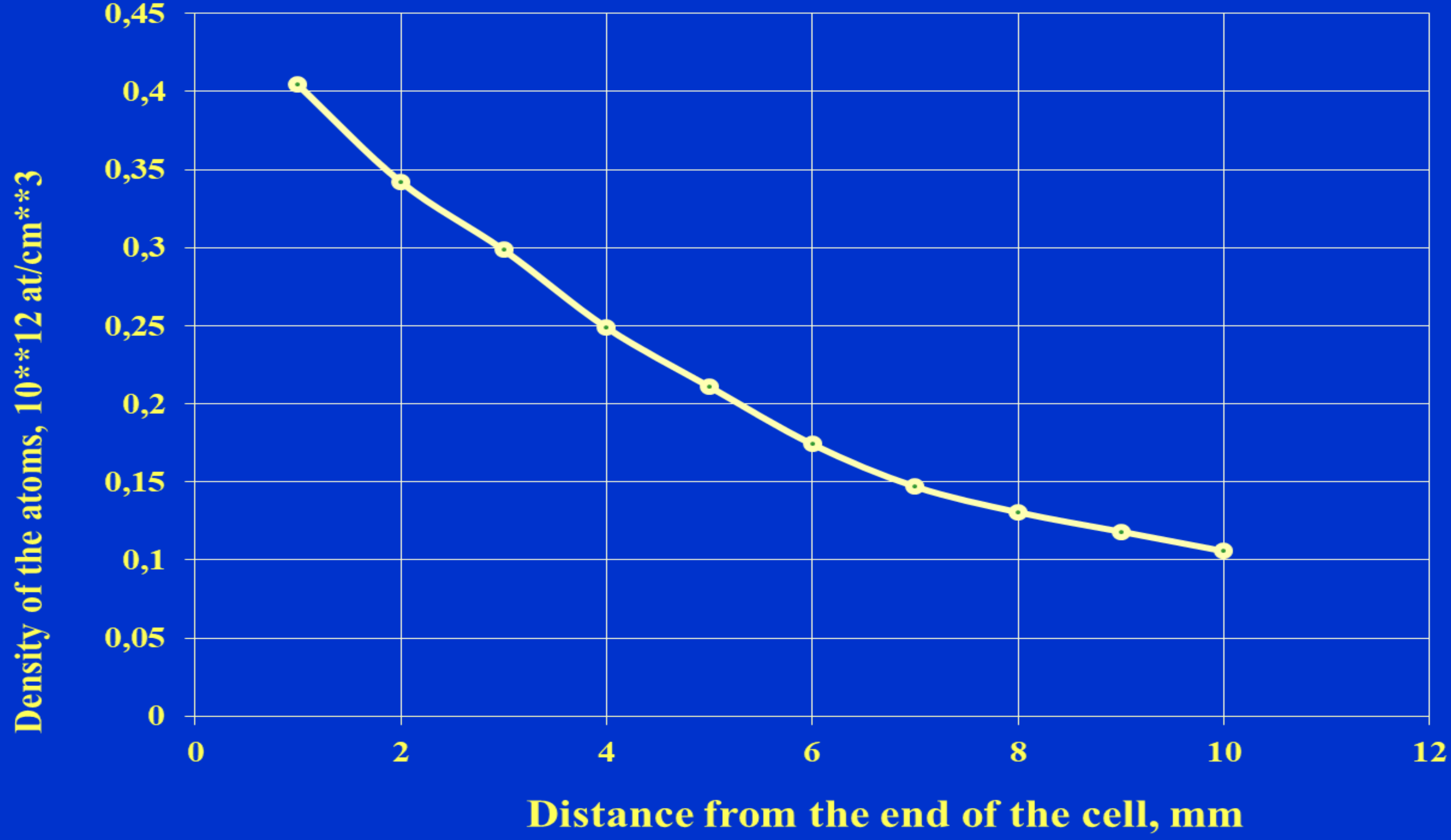


Number of wall collisions of atoms leaving the cell from one of its end vs the length of cell

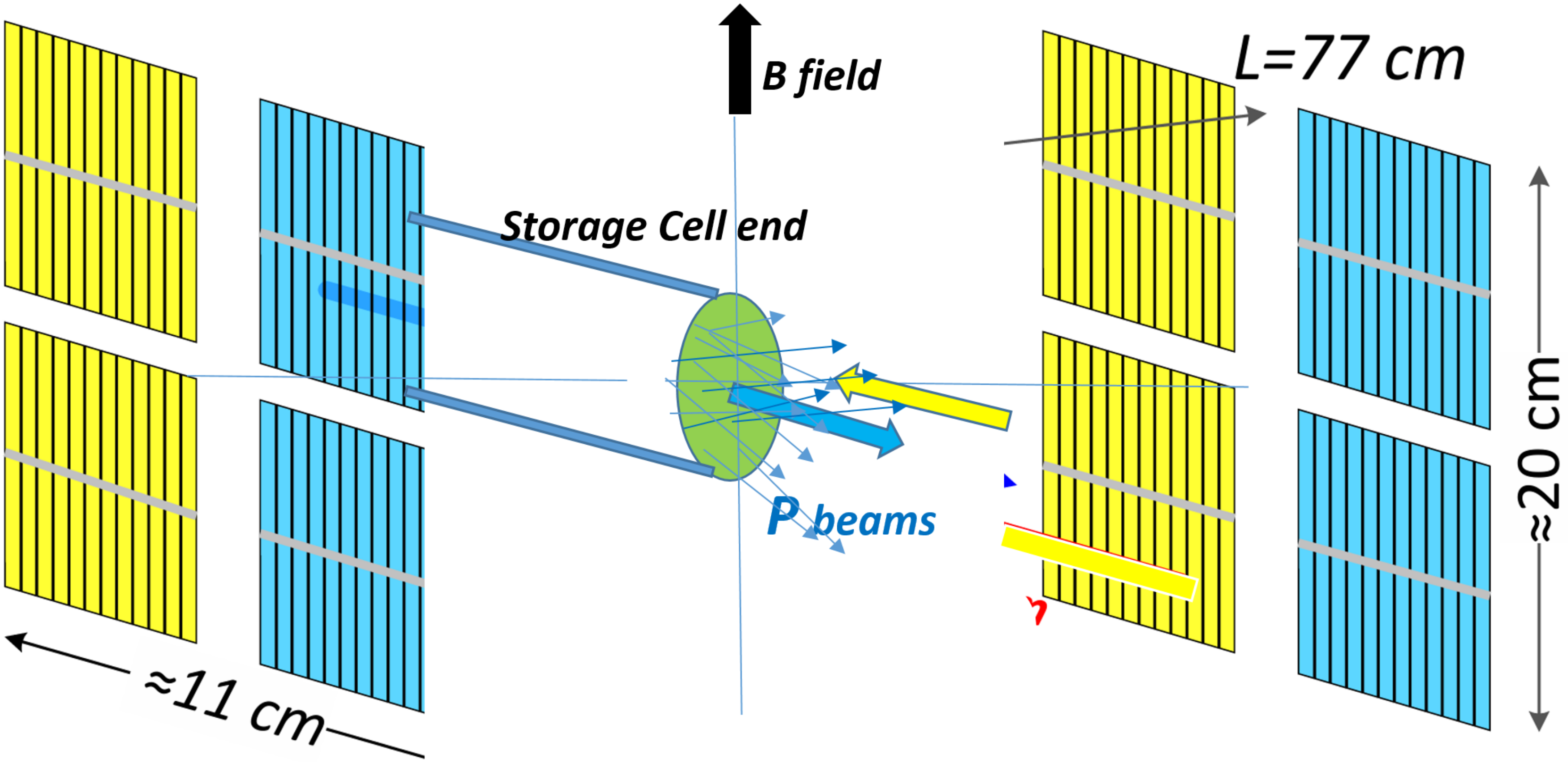


Density of atoms on the axis of the cell vs the distance from the end of the cell

$$\int_0^{10\,mm} n(l)dl = 0.22\,t_0$$



Possible detector of CNI at LHC

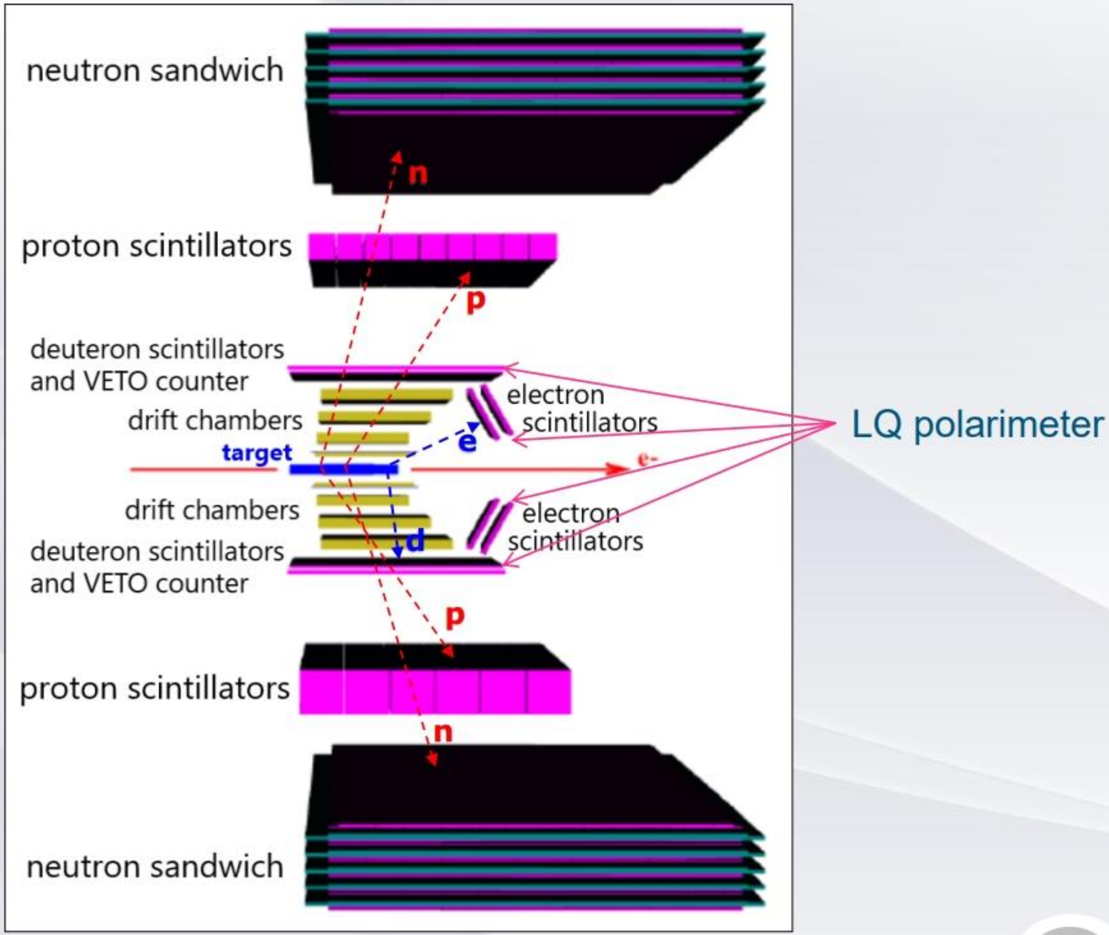


Detector view – present time

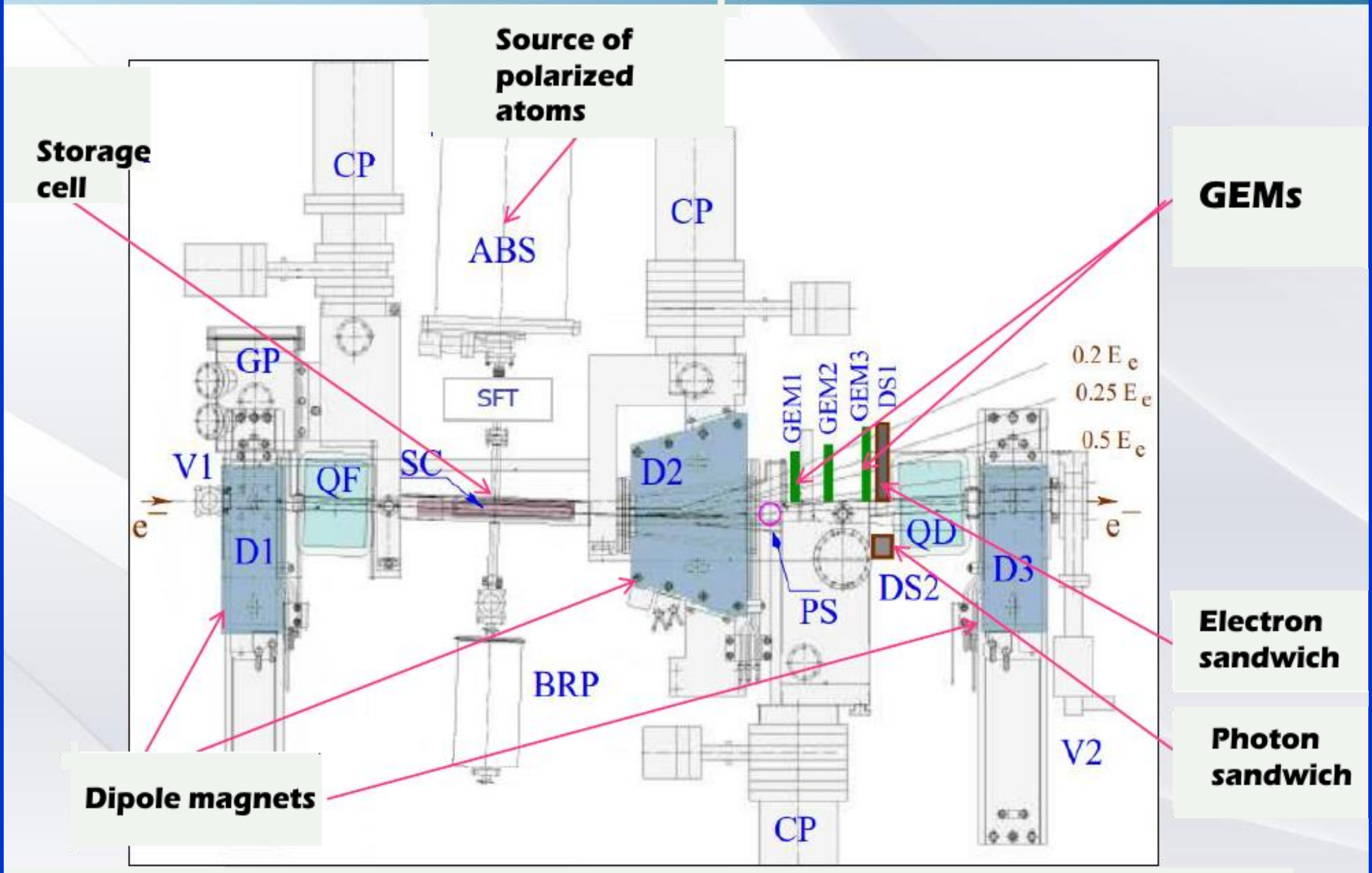
The detector system consists of two symmetrical arms for detecting proton and neutron in coincidence.

The tensor polarization of the target is measured using a LQ polarimeter.

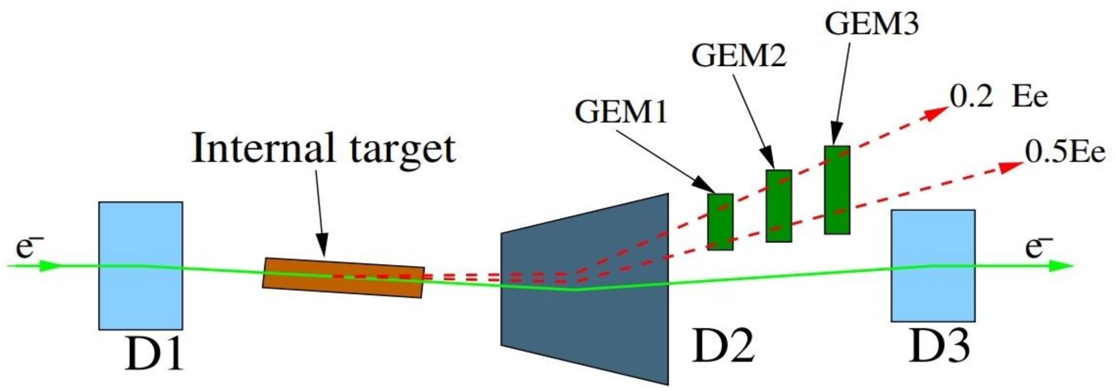
It consists of two symmetrically located sets of scintillation counters for detecting electron and deuteron in the process of elastic e-d scattering.



System of tagging photons — Top view



The Photons Tagging System at VEPP-3 storage ring



The photon tagging system, top view. D1, D2, D3: dipole magnets, GEM1, GEM2, GEM3: tracking detectors.

Physics of Particles and Nuclei, Volume 45, Issue 1, January 2014, Pages 338-340

The reported measurements were done using a polarized deuterium target and unpolarized photons.

The incident photons of the photoproduction reactions $\gamma d \to d\pi 0,\ pn\pi 0,\ pp\pi\text{-},\ pn$ are the quasi-real virtual photons arising from the electron scattering at small angle in these reaction.

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega}\left\{1 - \sqrt{\frac{3}{4}}\mathbf{P_z}\sin\theta_H\sin\phi_H \cdot \mathbf{T_{11}}(E\gamma,\theta_\pi^{CM}) + \sqrt{\frac{1}{2}}\mathbf{P_{zz}}\left[\frac{3\cos^2\theta_H - 1}{2}\cdot\mathbf{T_{20}}(E\gamma,\theta_\pi^{CM}) - \sqrt{\frac{3}{8}}\sin 2\theta_H\cos\phi_H \cdot \mathbf{T_{21}}(E\gamma,\theta_\pi^{CM}) + \sqrt{\frac{3}{8}}\sin^2\theta_H\cos 2\phi_H \cdot \mathbf{T_{22}}(E\gamma,\theta_\pi^{CM})\right]\right\},$$

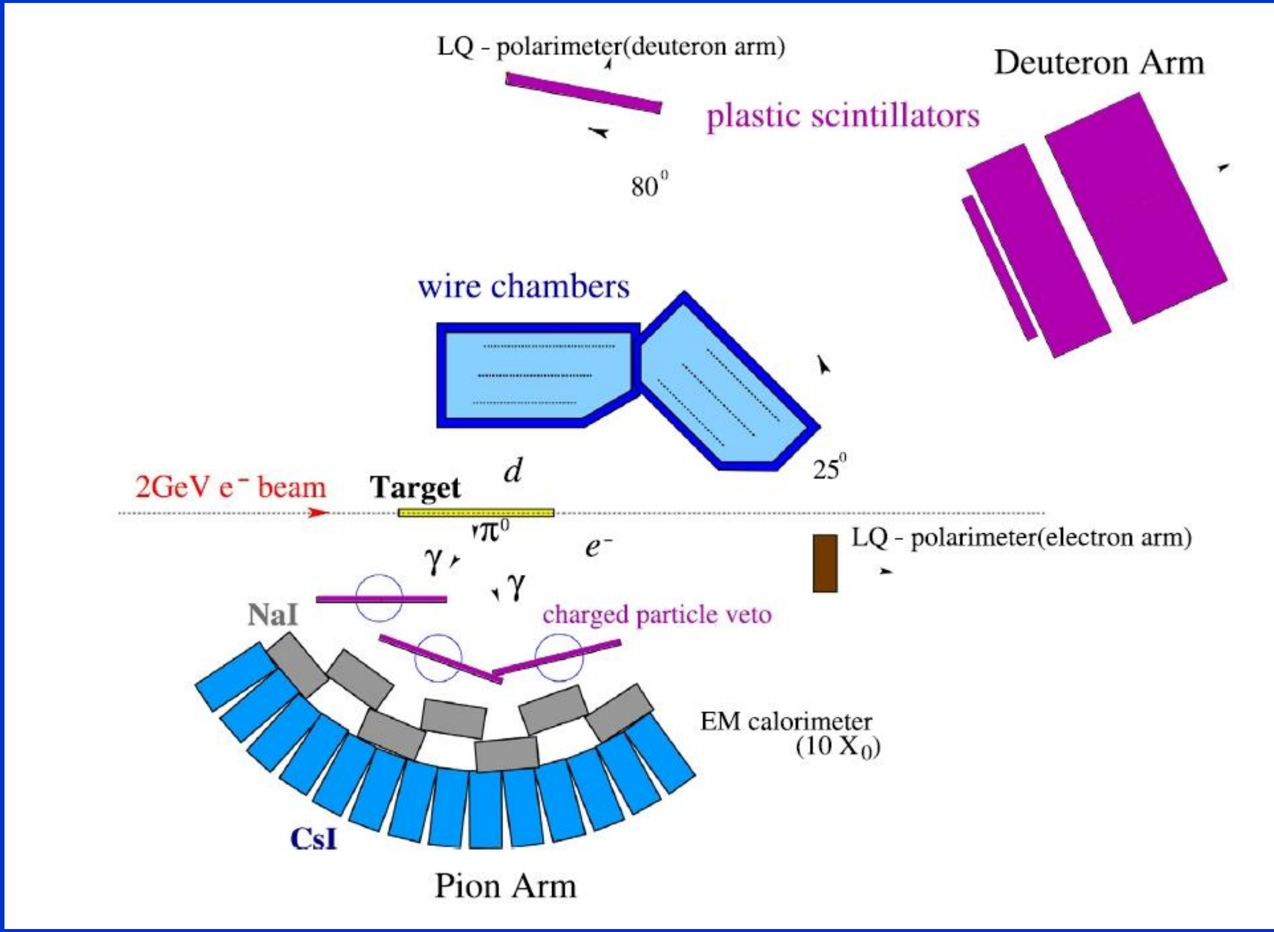
$$A^t = \sum_{i=0}^{2} d_{2i} T_{2i}$$

$$A^t = \sqrt{2}\,\frac{(N^+ - N^-)}{(N^- P_{zz}^+ - N^+ P_{zz}^-)}$$

Coherent photoproduction of a π0-meson on a deuteron

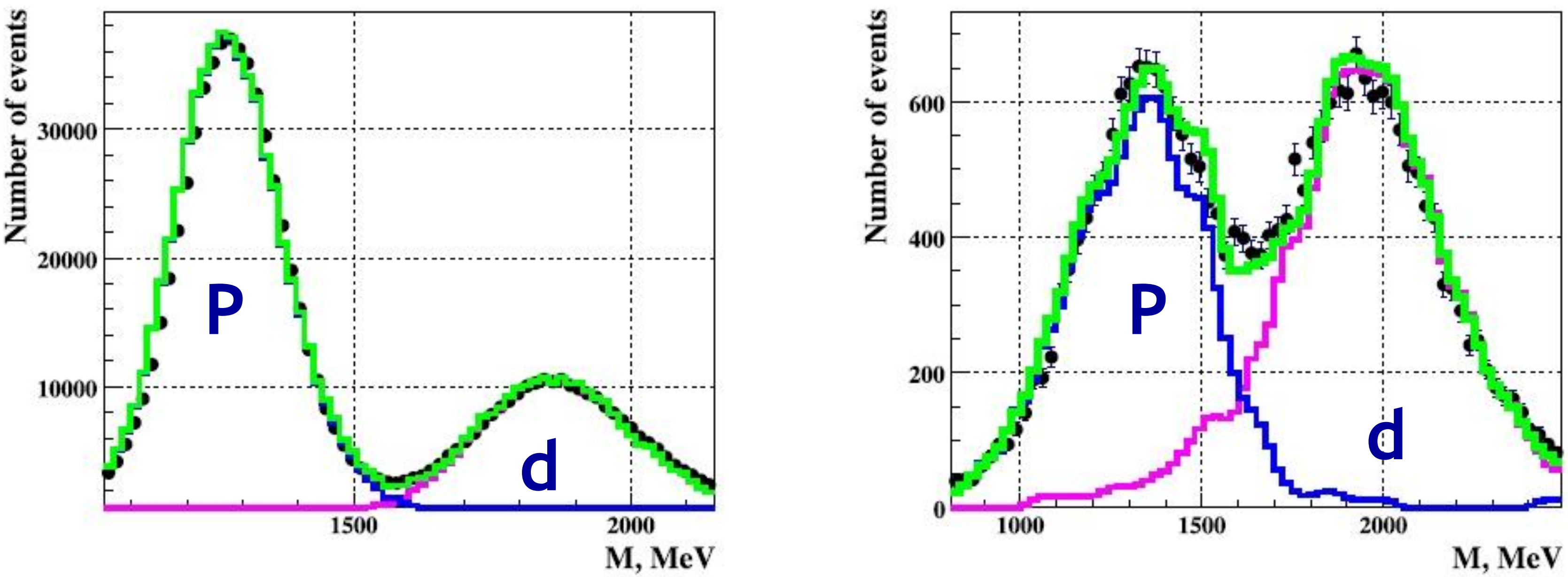
$$\gamma \vec{d} \rightarrow \pi^0 d$$

Eur. Phys. J. A (2020) 56:169



Scheme of the experiment 2013

Reconstructed particle masses distribution for the first (the left pane) and second (the right pane) scintillator. The points correspond to the experimental data, the magenta (blue) curve correspond to the GEANT4 simulation of the $\gamma d \rightarrow d\pi 0$ reaction (background reactions).



First scintillator

Second scintillator

A simple cut on the energy deposited in the NaI/CsI calorimeter, *E*cal > 100 MeV and demanded no-signal in the charge veto plastics were applied

Measurement of the tensor analyzing power T20 for the reaction $\gamma \vec{d} \rightarrow d\pi 0$ Eur. Phys. J. A (2020) 56:169

Dependences of the T20 component of tensor analyzing power of the reaction γ d → dπ0 on the photon energy for the polar angle of pion emission in the center-of-mass system of 110◦ and 130◦. Theoretical calculations:

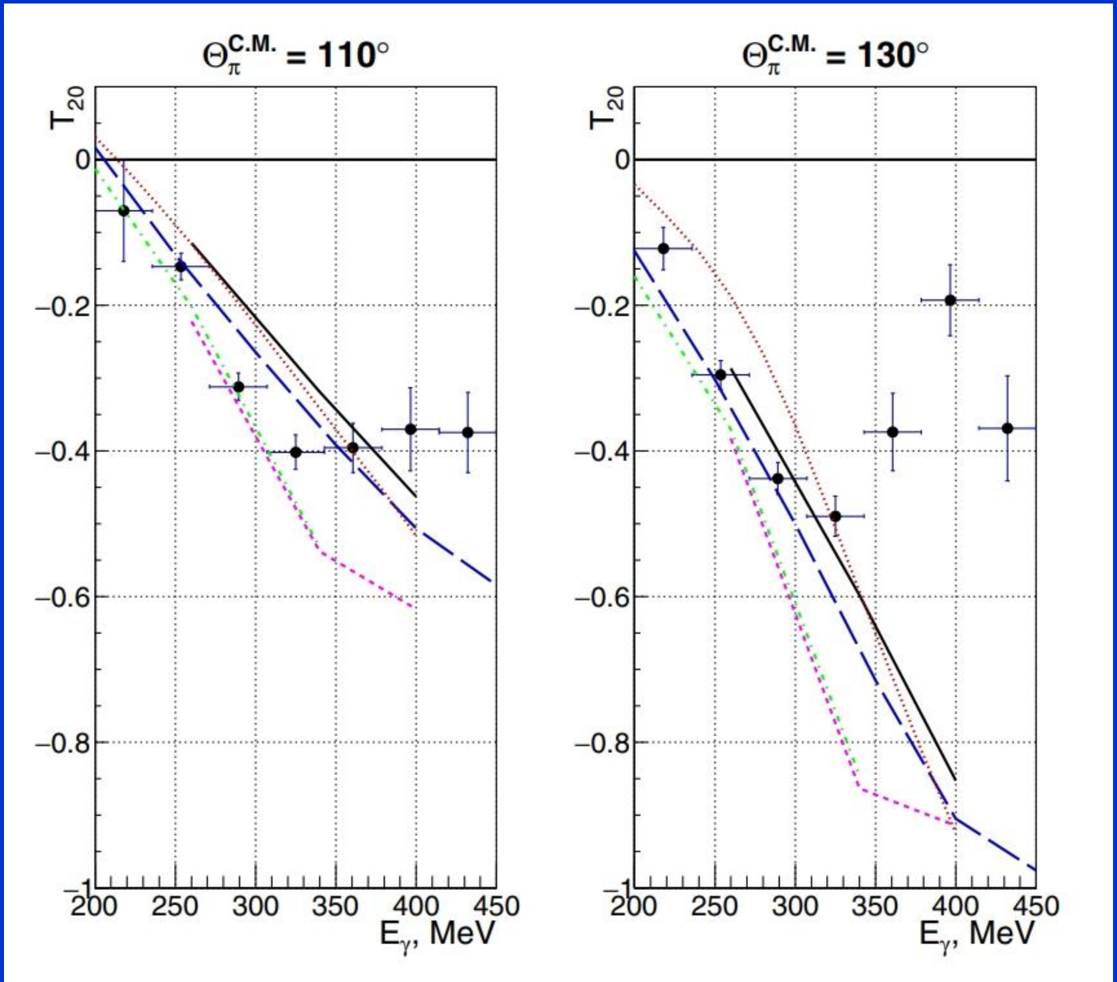
magenta (short-dashed) – P. Wilhelm, H. Arenhövel, Nucl. Phys. A 609, 469 (1996) ,

green (dash-dotted) – S.S. Kamalov et al. L. Phys. Rev. C 55, 98 (1997)

red (dotted) – E.M. Darwish et al. Mosc. Univ. Phys. Bull. 74, 595 (2019)

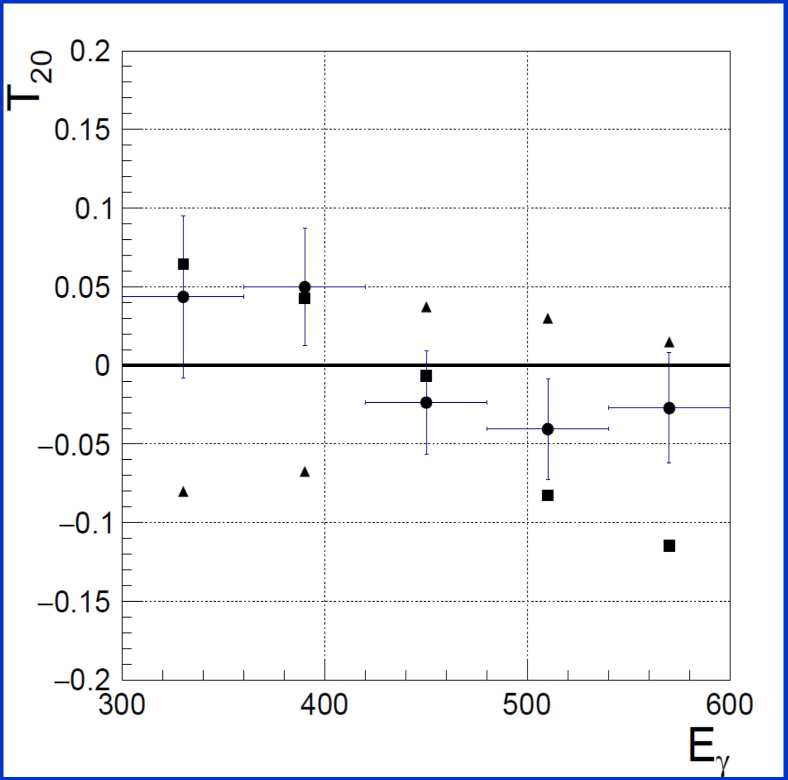
black (solid) – M.I. Levchuk, Private communication, (2013)

blue (long-dashed) – A.I. Fix, Private communication, (2013)



Measurement of the tensor analyzing power T20 for the reaction $\gamma \vec{d} \rightarrow pn\pi0$

The role of final-state interaction in tensor polarization effects of the reaction γd → pnπ0



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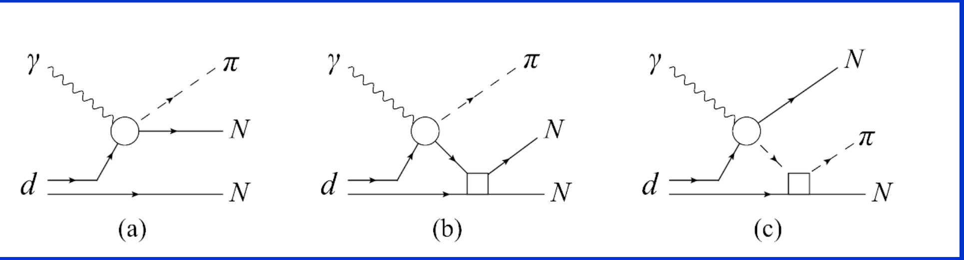
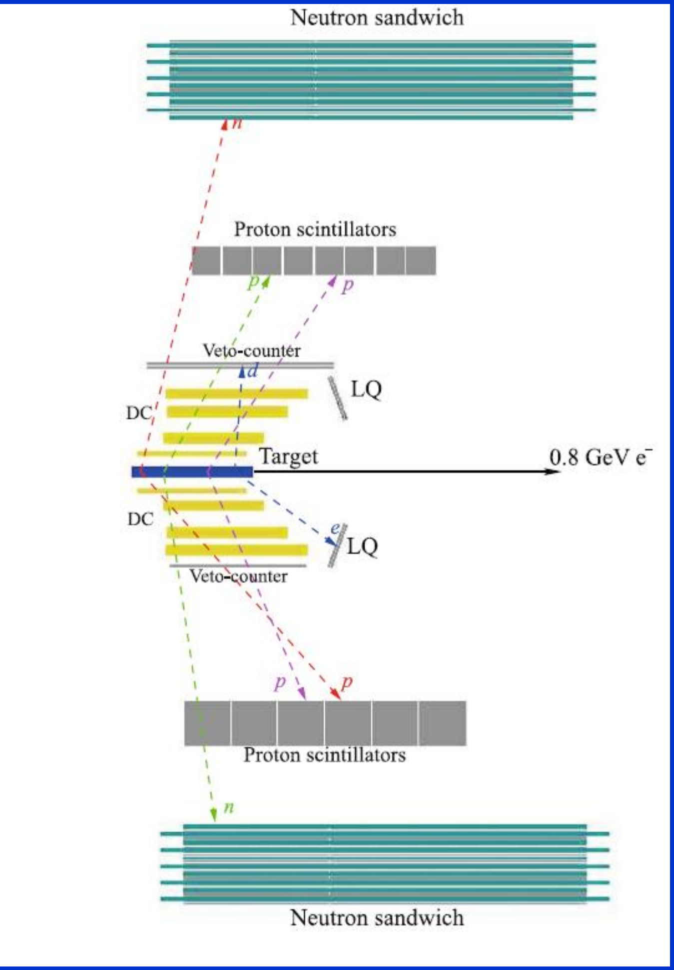
experiment 2002 -2003

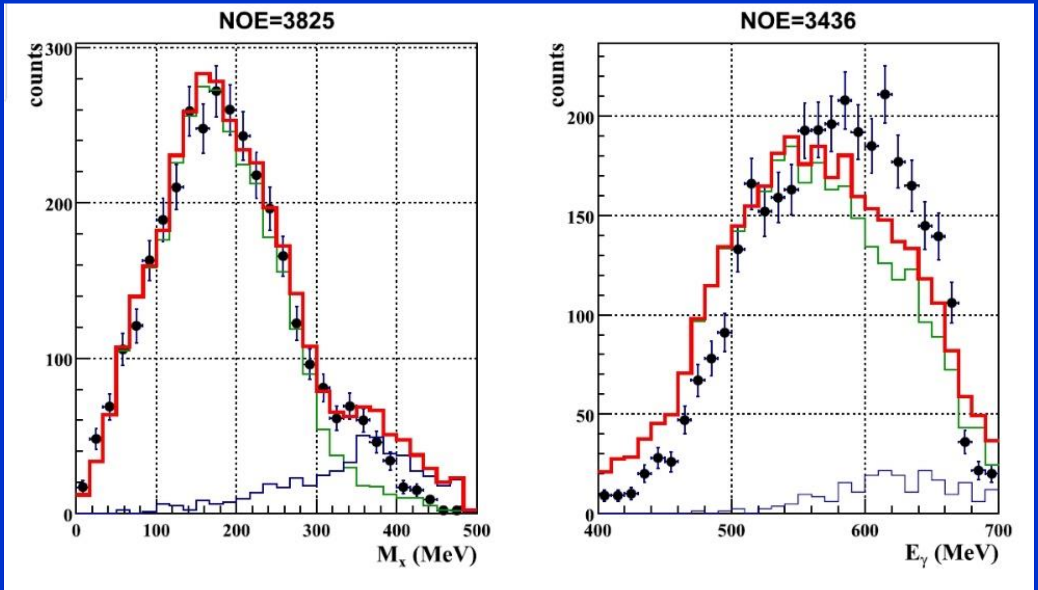
Photon-energy dependence of the tensor analyzing power component T_{20} for the incoherent reaction $\gamma d \rightarrow \pi^0 pn$. Circles: experimental data; triangles: impulse approximation; squares: calculations including final-state interactions



Measurement of the $T20$ Component of the Tensor Analyzing Power of the Incoherent Photoproduction $\gamma d \rightarrow pp\pi^-$ of a π– Meson on a Deuteron for photon energies 400 –700 MeV (exp 2023)

Phys. Lett. B 860 (2025) 139166





Distribution of the reconstructed missing mass Mx (leftpanel) and the initial photon energy $E\gamma$ (right panel). The $E\gamma$ data refer to Mx < 340 MeV.
The points are the experimental data, the color curves represent the GEANT4 simulation: the green curve is the reaction $\gamma d \rightarrow pp\pi^-$, the blue curve is the background reactions, and the red curve shows the sum of all reactions.

The experiment was carried out with the use of tagged quasi-real photons and two-proton coincidence.

Result on T_{20} measurement

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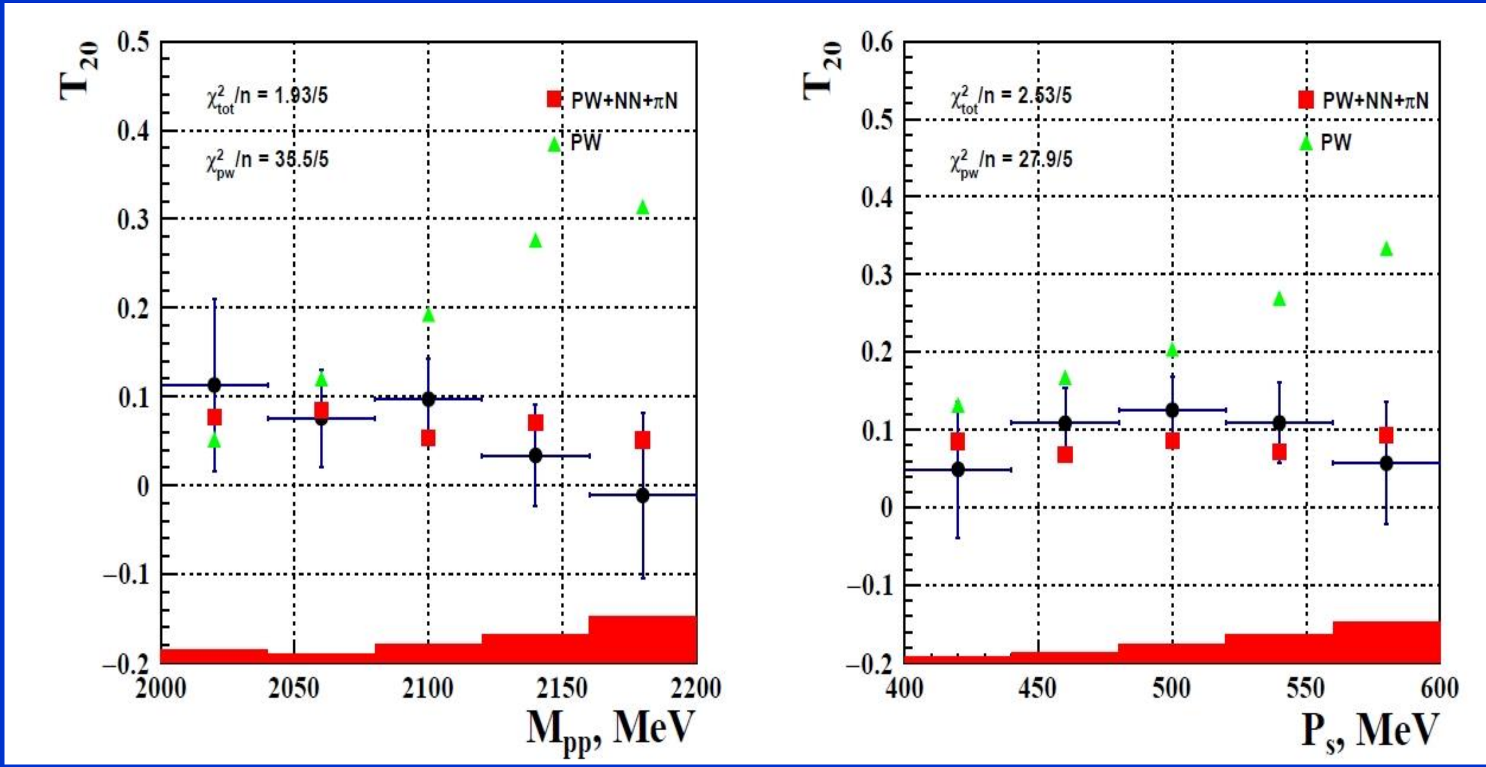
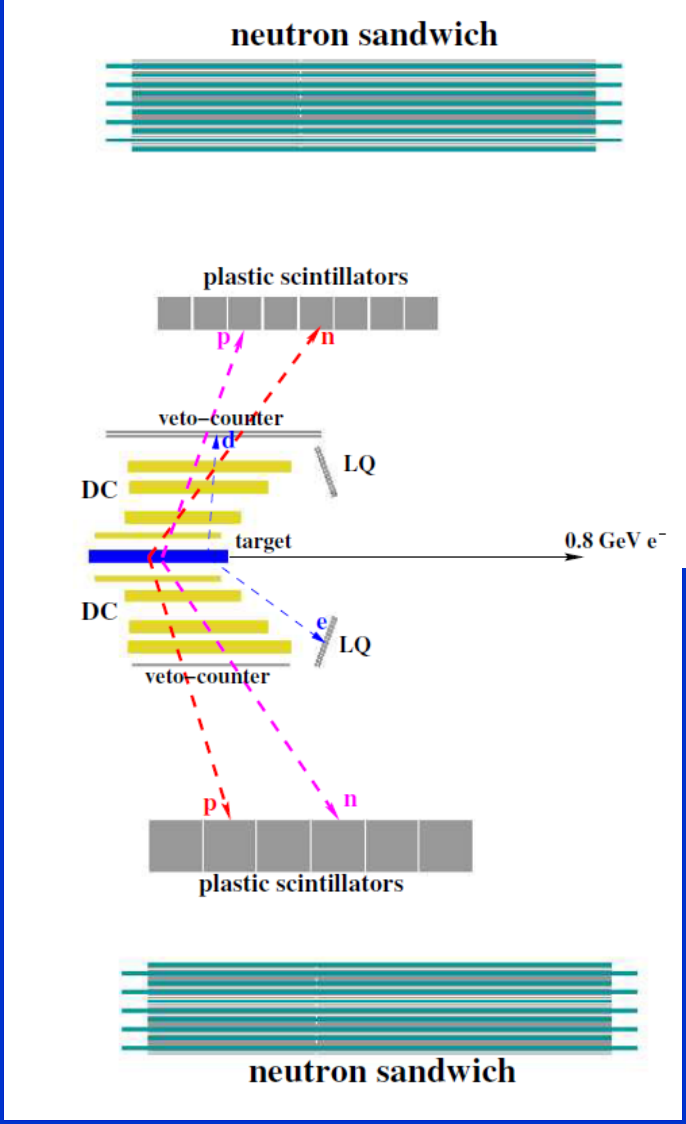
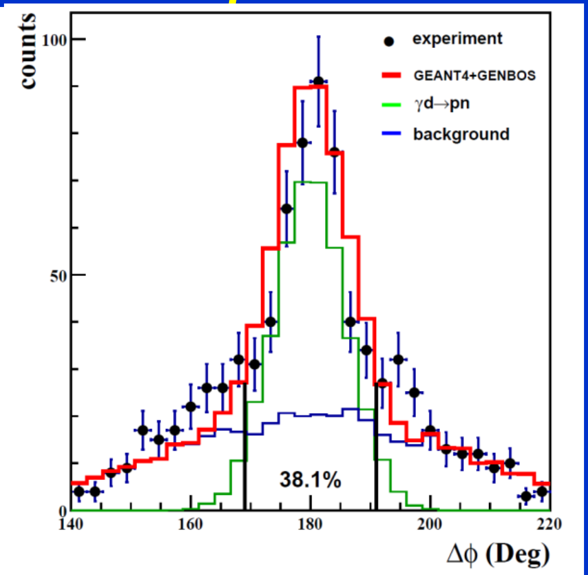
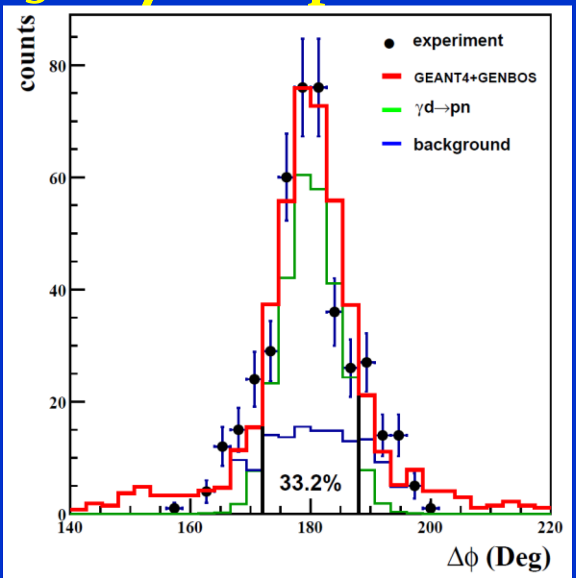


Tensor analyzing power component T_{20} for the reaction $\gamma d \to \pi^- pp$ as a function of the proton-proton invariant mass M_{pp} (left panel) and the momentum of the slow proton (right panel). The black filled circles represent the experimental results. Statistical and systematic uncertainties are indicated by the red lines shown at the bottom of each panel. The red squares and green triangles correspond to simulations based on the spectator model, with and without inclusion of πN and NN rescattering in the final state, respectively.

Measurement of the tensor analyzing power T20 for a deuterons photodisintegration above the first resonance region $\gamma d \to pn$

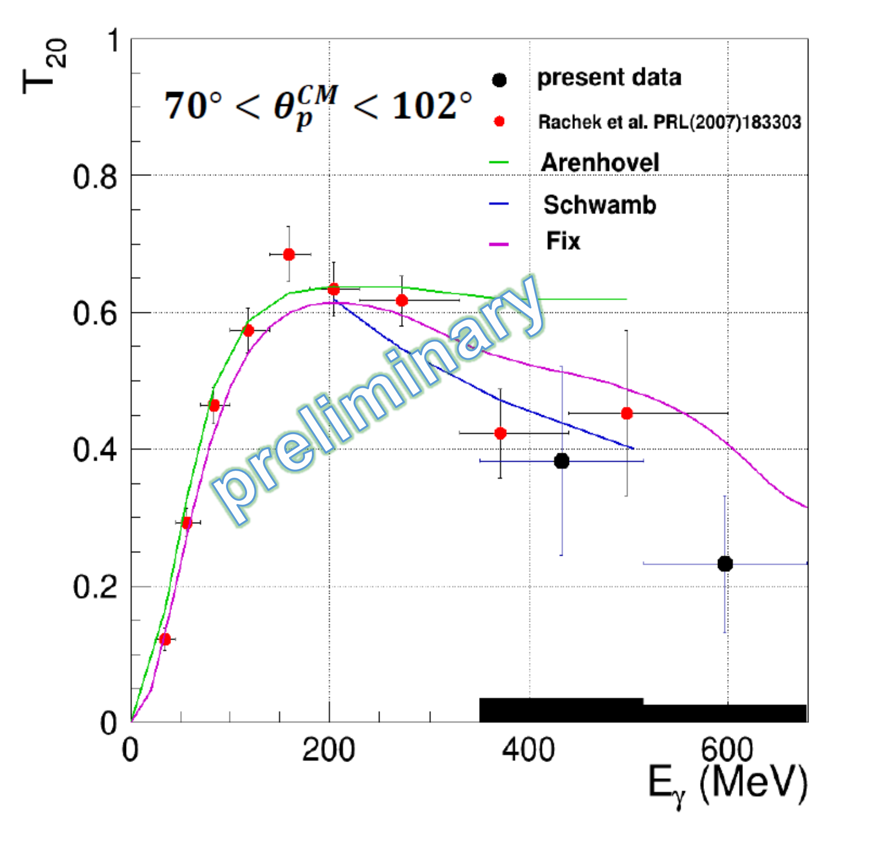






Tagged quasi-real photons, proton and neutron were detected in coincidence.

Distribution of Δφ = φp − φn in the case where the proton is registered by the lower arm and the neutron by the upper arm (left panel) and where the proton is registered by the upper arm and the neutron by the lower arm (right panel). The points show the experimental data. The GEANT4 simulations are plotted by the curves: the green curve is the γd → pn reaction, the blue curve shows the contribution of the background reactions (γd → pnπ−π+, γd → pnπ0 andγd → pnπ0π0), and the red curve is the sum of all reactions.



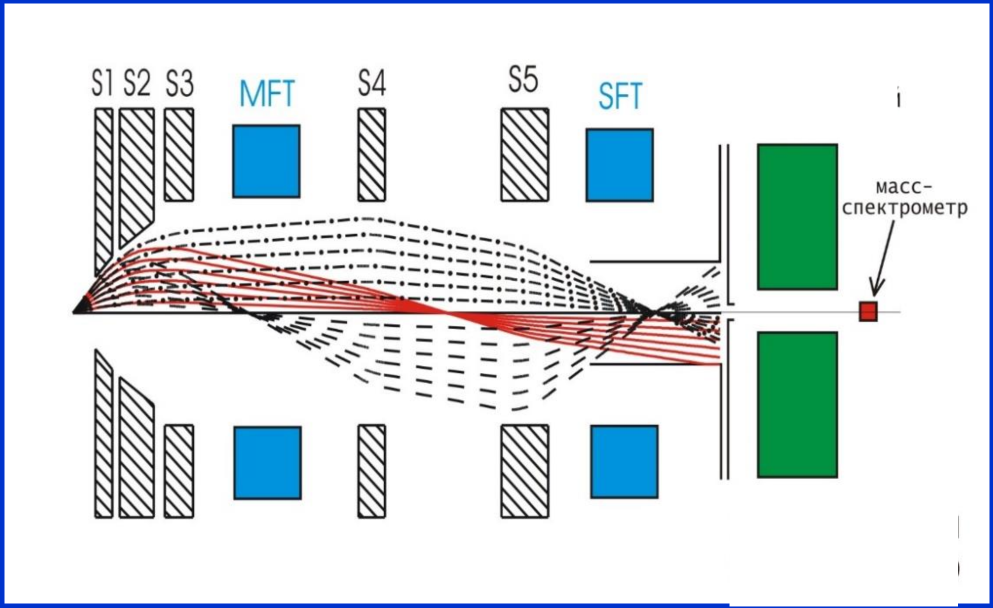
T_{20} for $\gamma d \rightarrow pn$ vs. laboratory photon energy E_γ, averaged over $\theta_p = 70° - 102°$. Black circles: this work; red circles: earlier data (2002-2003) [Ref]. Error bars: statistical only. Curves: theoretical predictions by Arenhövel [H. Arenhövel and M. Sanzone, Few-Body Syst. Suppl. 3, 1 (1991)], Schwamb [M. Schwamb, Phys. Rep. 485, 109 (2010)] and Fix [Phys. At. Nucl. 88, 1235 (2025)].

Nearest plans

1. Continue processing data of the experiment $\gamma d \longrightarrow pn$, including information from neutron calorimeters.
2. Continue the experiment for the energy of γ in the range 700 - 1000 MeV at the energy of electron beam 1250 MeV.

Thank for your attention

Focusing magnets



Permanent magnets
B=1.6 T
Superconducting
B=4.8 T

$\Delta\Omega = \pi * \alpha^2 = \pi * \mu * B/\kappa T$

$B = 1.6$ T	$\Delta\Omega \sim 1.5 * 10^{-2}$ sr	$\alpha \sim 0.07$ rad
$B = 4.8$ T	$\Delta\Omega \sim 4.5 * 10^{-2}$ sr	$\alpha \sim 0.21$ rad

Nucl. Instrum. Methods, 495 (2002) 8.