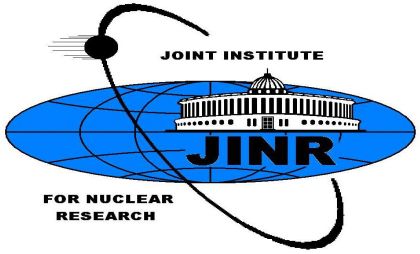
Results of DSS collaboration with unpolarized and polarized deuteron beams at Nuclotron



V.P.Ladygin on behalf of the DSS collaboration

5-th Nuclotron Users workshop, 5-6 October, 2017

Outline

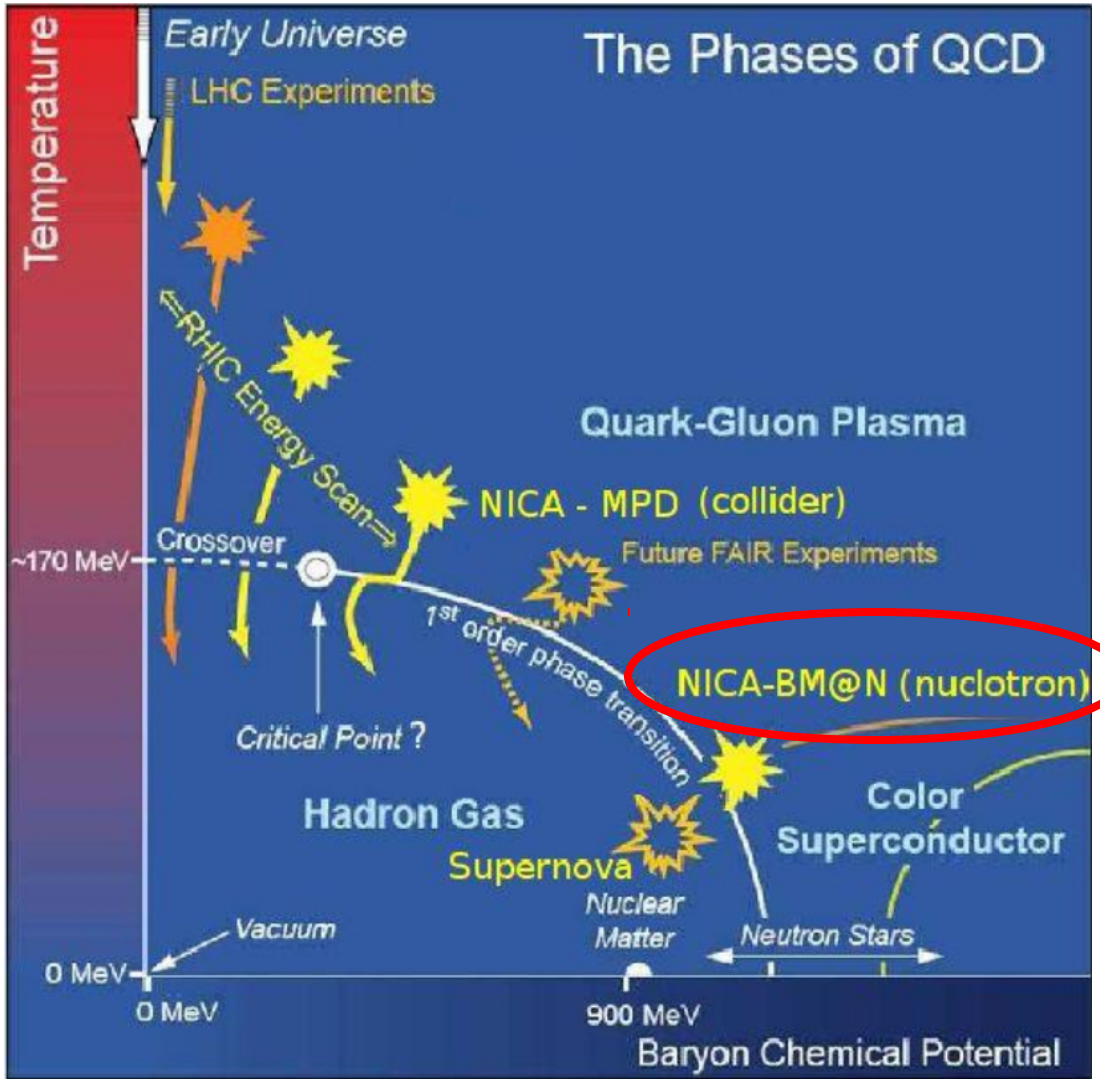
1. Motivation
2. Results on dp-elastic scattering obtained at Nuclotron JINR with unpolarized beam
3. First results on the energy scan of the vector Ay and tensor Ayy and Axx analyzing powers in dp-elastic scattering at Nuclotron
4. Further plans at Nuclotron
5. Conclusion

DSS collaboration:
Bulgaria-JINR-Japan-Romania-Russia-Slovakia

Motivation of the dp interaction studies

- **Nucleon-nucleon interaction at short distances (including its mass off-shell behaviour)**
- **Relativistic effects**
- **Transition to the nonnucleonic degrees of freedom**
- **Contribution of three-nucleon forces (3NFs)**

stalled from E.L.Bratkovskaya



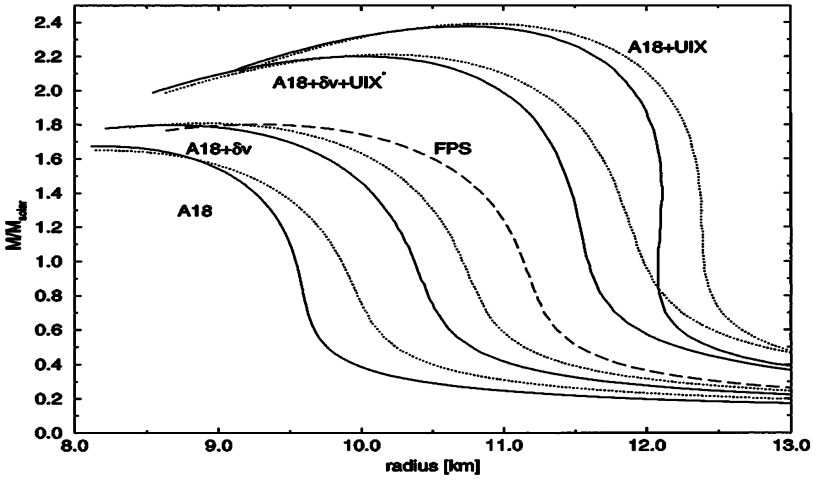
Study of the phase transition from hadronic to partonic matter – Quark-Gluon-Plasma

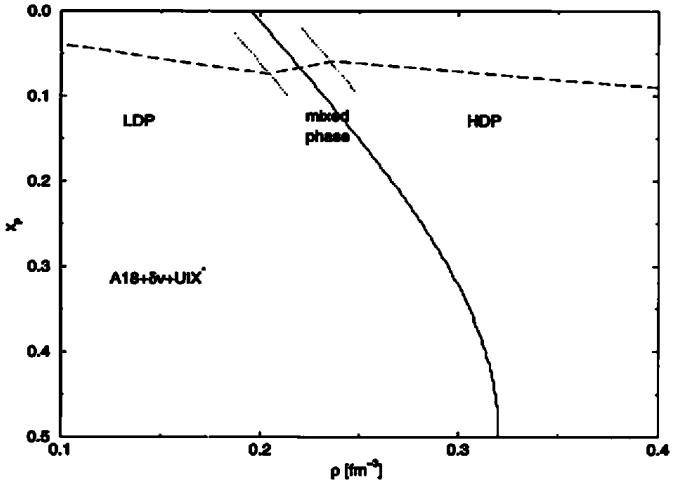
Many theoretical approaches: transport, thermodynamics etc. transferred to the event generators UrQMD, HSD, LAQGSM ...

Lattice QCD calculations

Few nucleons systems as a tool for dense matter studies

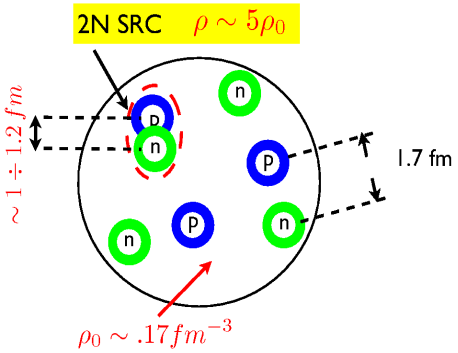
Alternative way to obtain the information on the EOS at extreme densities (neutron stars) is the studies of the few nucleon systems.

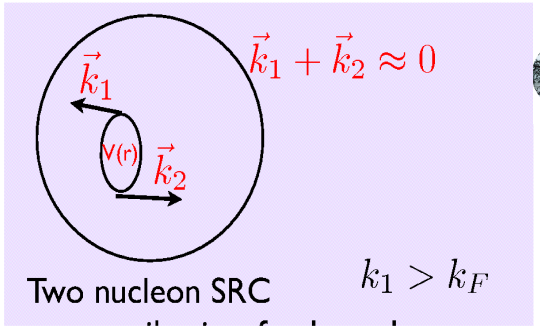




Relativistic effects in 2NF and contribution of 3NF play very important role. (A.Akhmal et al, Phys.Rev. C58 (1998) 1804)

Short range correlations (SRCs)





Summary of the theoretical analysis of the experimental findings
practically all of which were predicted well before the data were obtained

More than ~90% all nucleons with momenta k≥300 MeV/c belong to two nucleon SRC correlations BNL + Jlab +SLAC

Probability for a given proton with momenta 600> k > 300 MeV/c to belong to **pn** correlation is ~ 18 times larger than for **pp** correlation BNL + Jlab

Probability for a nucleon to have momentum > 300 MeV/c in medium nuclei is ~25% BNL + Jlab 04 +SLAC 93

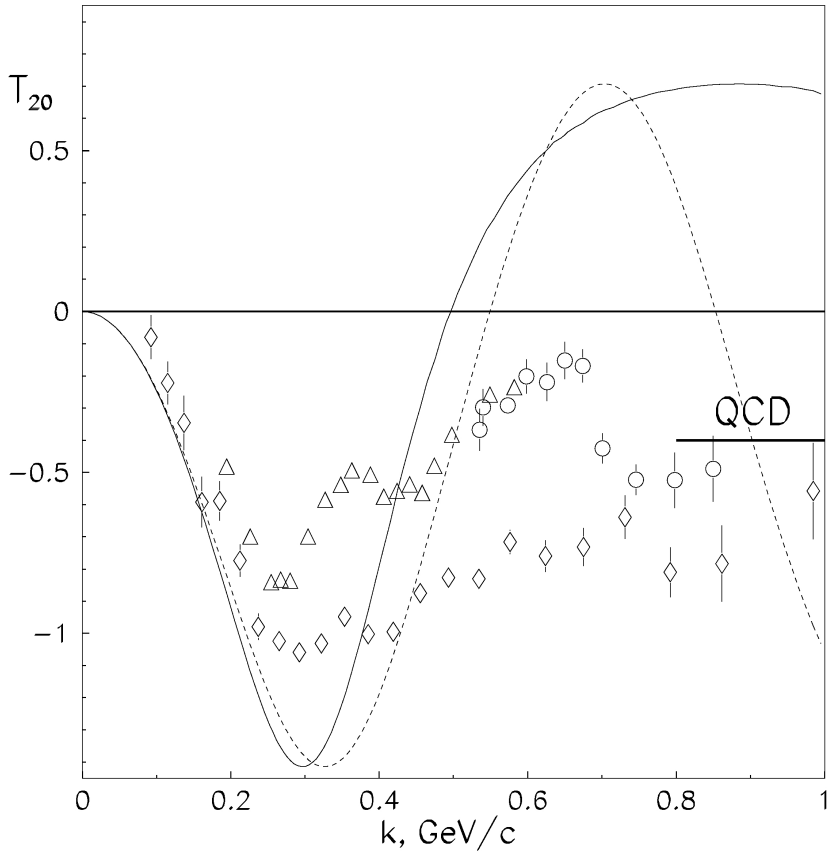
Probability of non-nucleonic components within SRC is small - < 20% - 2N SRC mostly build of two nucleons not 6q, ΔΔ,... BNL + Jlab +SLAC

Three nucleon SRC are present in nuclei with a significant probability Jlab 05

Poor data base on the spin parts of the 2N and 3N short-range correlations. This motivates the neccessity to study light nuclei structure at short distances.

Experiments at Nuclotron allow to reach $p_T \sim$ 1 GeV/c

Non-nucleonic degrees of freedom



When the distances between the nucleons are comparable with the size of the nucleon, the nucleon-nucleon interaction is a non-local.

The fundamental degrees of freedom, quark and gluons in the frame of QCD, begin also to play a role at the internucleonic distances comparable with the size of the nucleon.

They can manifest as ΔΔ, NN*, N*N*, 6q etc.components.

Data:

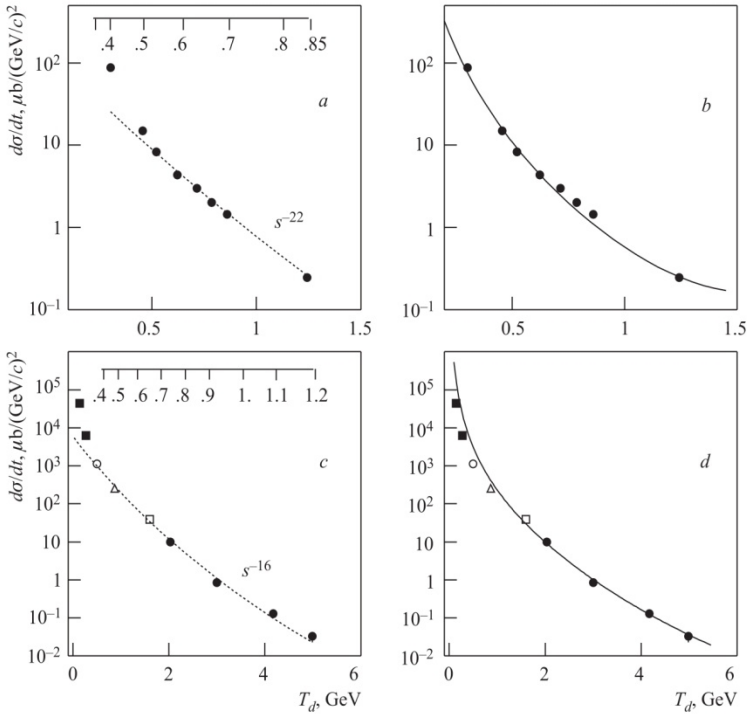
V.Punjabi et al., Phys.Lett.B350 (1995) 178
L.S.Azhgirey et al., Phys.Lett.B391 (1997) 22
L.S.Azhgirey et al., Phys.Lett.B387 (1996) 37

Fundamental (quark) degrees of freedom

At high energy s and large transverse momenta p_t the constituent counting roles (CCR) predict the following behavior of the differential cross section for the binary reactions:

$$\frac{d\sigma}{dt}(ab\to cd)=\frac{f(t/s)}{s^{n-2}} \quad ; \quad \mathbf{n = N_a+N_b+N_c+N_d}$$

(Matveev, Muradyan, Tavkhelidze, Brodsky, Farrar et al.)



Yu. N. Uzikov

JETP Lett, 81 (2005) 303-306

For the reaction **dd → ^{3}Hen**

$$N_A+N_B+N_C+N_D-2=22$$

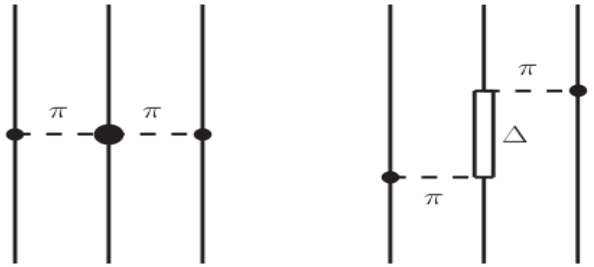
For the reaction **dp → dp**

$$N_A+N_B+N_C+N_D-2=16$$

The regime corresponding to CCR can occur already at $T_d \sim 500$ MeV

Three Nucleon Forces

- **Modern NN potentials (CD-Bonn, AV-18, Njimegen etc.) accurately reproduce the NN data set up to about 350 MeV. However they fail in the description of the triton binding energy and data on unpolarized dp-elastic scattering and breakup.**
- **Incorporation of three nucleon forces (3NF), when interaction depends on the quantum numbers of the all three nucleon, allows to reproduce the binding energy of the three-nucleon bound systems and the data on unpolarized dp- interaction.**

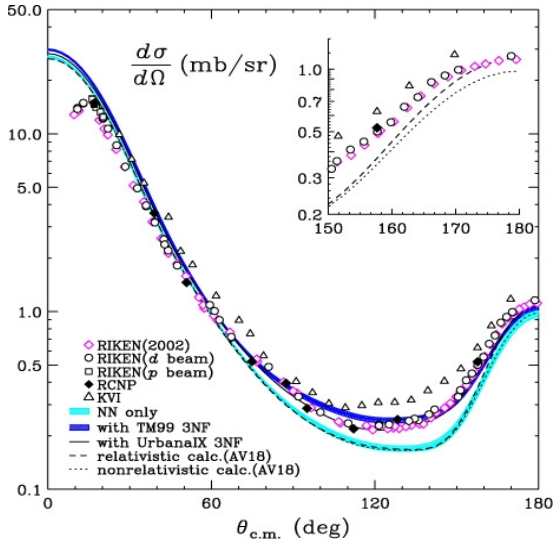


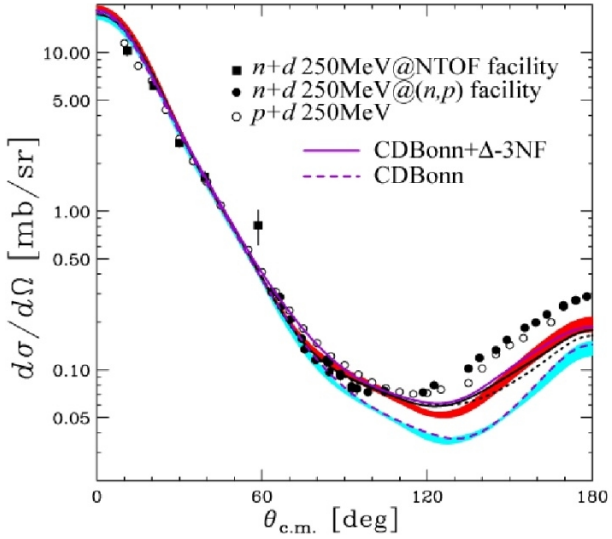
- Tucson-Melbourne
- Brazil
- Urbana-IX
- Fujita-Miyazawa ($N\Delta$)
- Chiral Effective Field Theory

Needs to be very careful: according to the theorem of W.N.Polyzou and W.Gloeckle, Few Body Syst. 9 (1990) 97, off-shell behaviour of 2NF can imitate 3NF effect.

Triton binding energy without 3NF:
Y.Fujiwara et al., Phys.Rev.C66 (2002) 021001(R)

Cross section in dp- elastic scattering at intermediate energies





The differential cross section in elastic Nd scattering at the energy of 135 (left figure) and 250 (right figure) MeV/u.

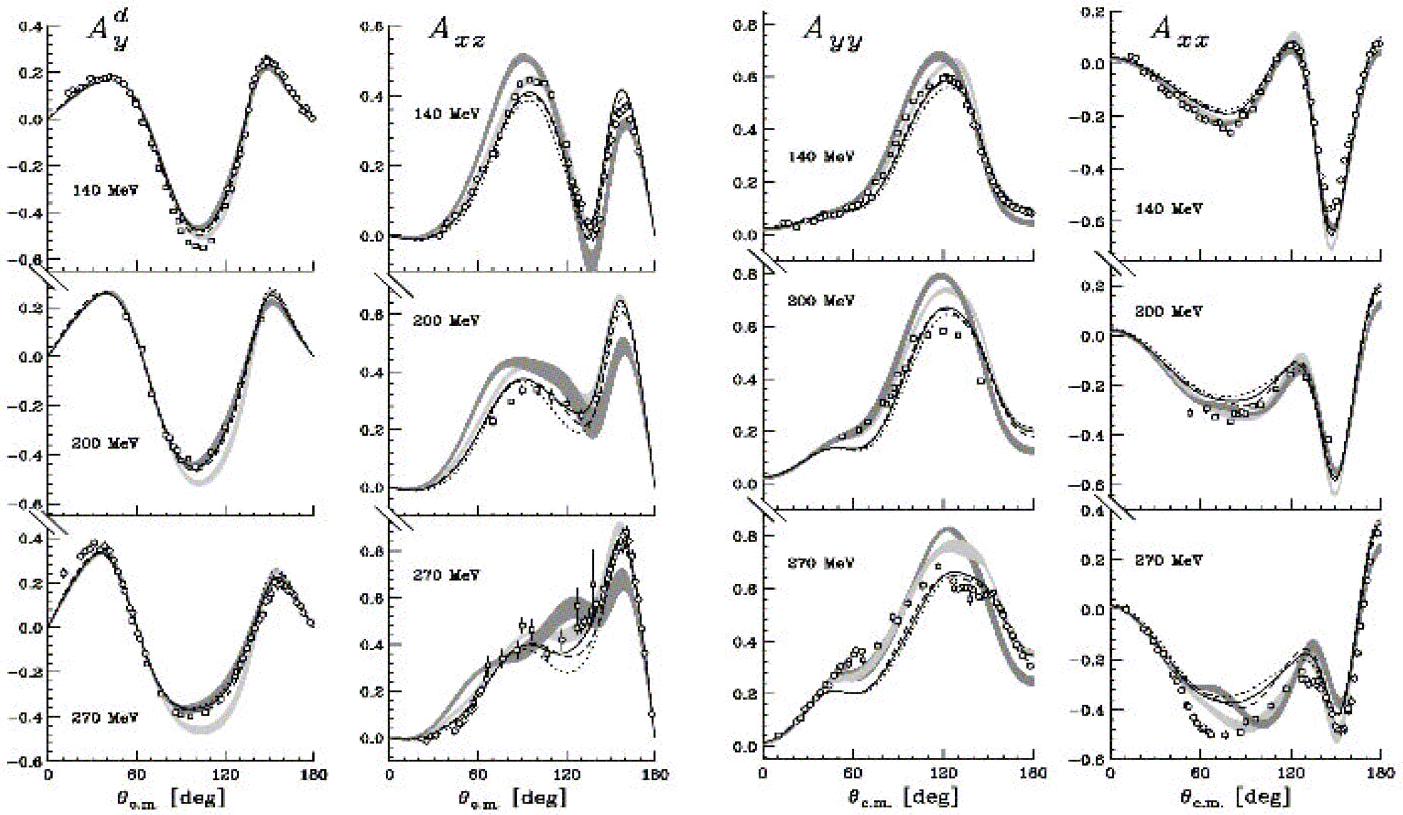
K. Sekiguchi et al., Phys. Rev. Lett. 95, 162301 (2005)

K. Hatanaka et al., Phys. Rev. C 66, 044002 (2002)

The cross section data for dp- elastic scattering are reproduced well up to 150 MeV taking into account 3NF. Manifestation of three-nucleon forces effect in the cross-section of dp-elastic scattering at this energy: up to 30% in the vicinity of Sagara discrepancy.

But the problems in the description are at higher energies.

Deuteron analyzing powers in dp- elastic scattering at intermediate energies (140, 200, 270 MeV)



Polarization data for dp- elastic scattering are not described even with the 3NFs inclusion (except for Ay).

The spin part of 3NFs is missed!

Status of dp- elastic scattering

Inclusion of modern 3NFs allows to describe cross section and deuteron vector analyzing power of dp- elastic scattering up to 135 MeV/nucleon, while the tensor observables are not described.

The data at higher energies (up to 300 MeV/nucleon) are not described even taking into account relativistic effects.

The reason of the discrepancy is nowadays called the importance of the short range 3NFs which are still not included.

1. The systematic study of hadronic reactions induced by deuterons at Nuclotron will allow to study the structure of 2N and 3N forces, including their short-range parts.

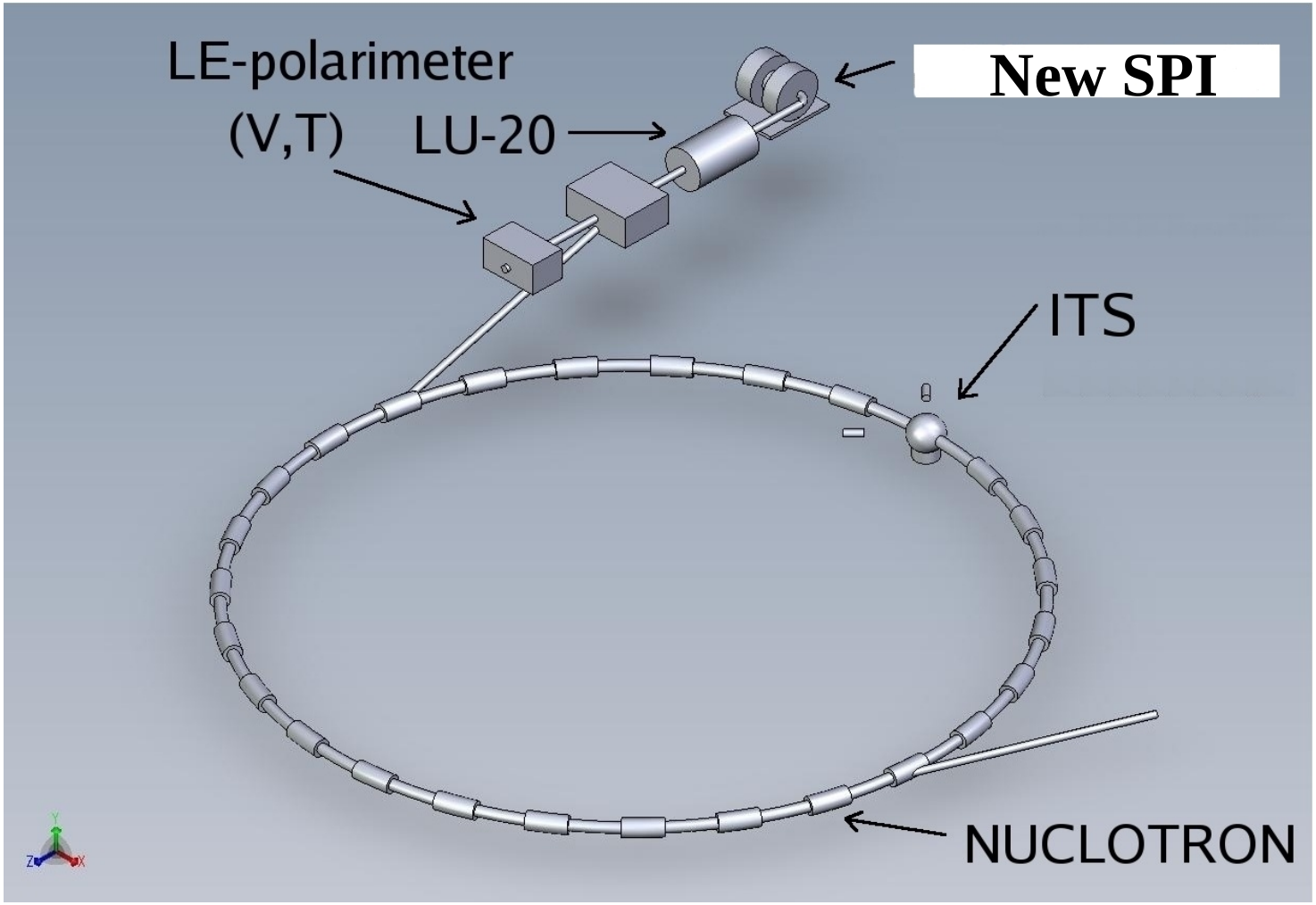
2. Development of the relativistic models for the description of these reactions is required.

The purpose of the **DSS** experimental program is to obtain the information about 2NF and 3NF (*including their spin – dependent parts*) from two processes:

1.dp-elastic scattering at the energies between 300 - 2000 MeV;

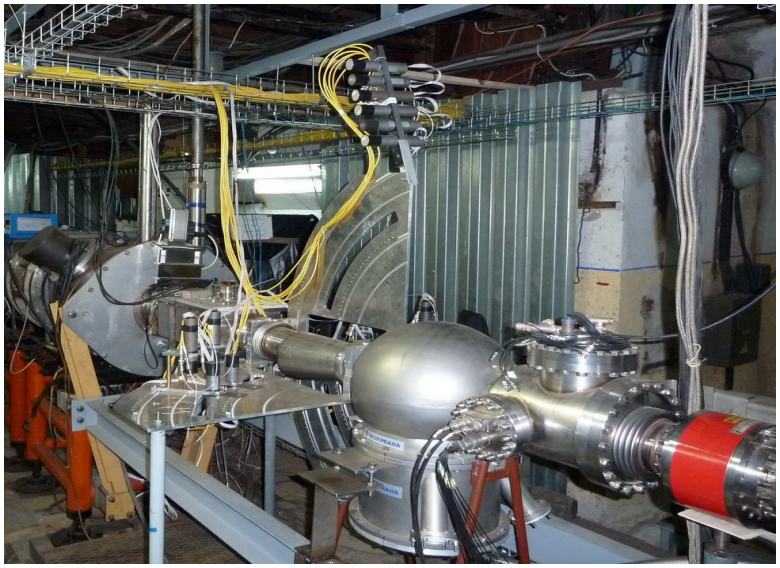
2.dp-breakup with registration of two protons at deuteron energies of 300 - 500 MeV.

Nuclotron-M accelerator complex



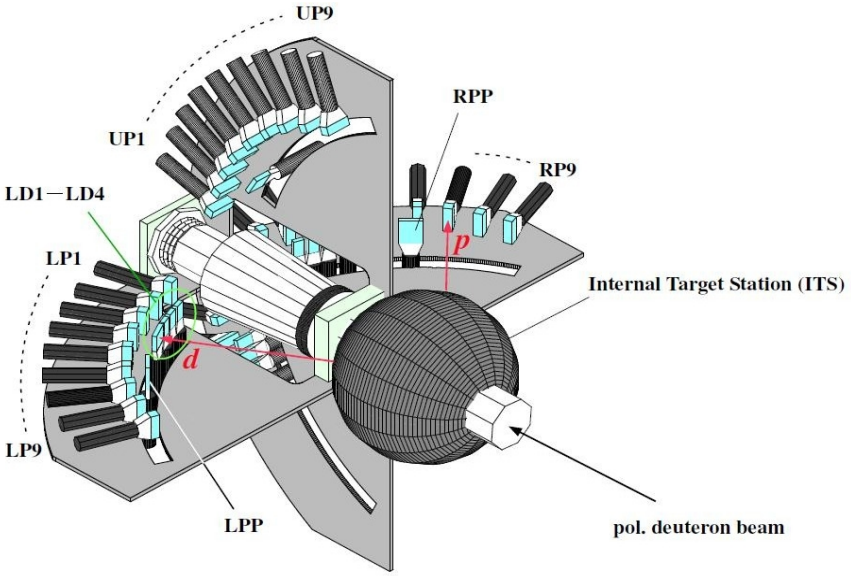
Experiments at Internal Target Station at Nuclotron

DSS-project



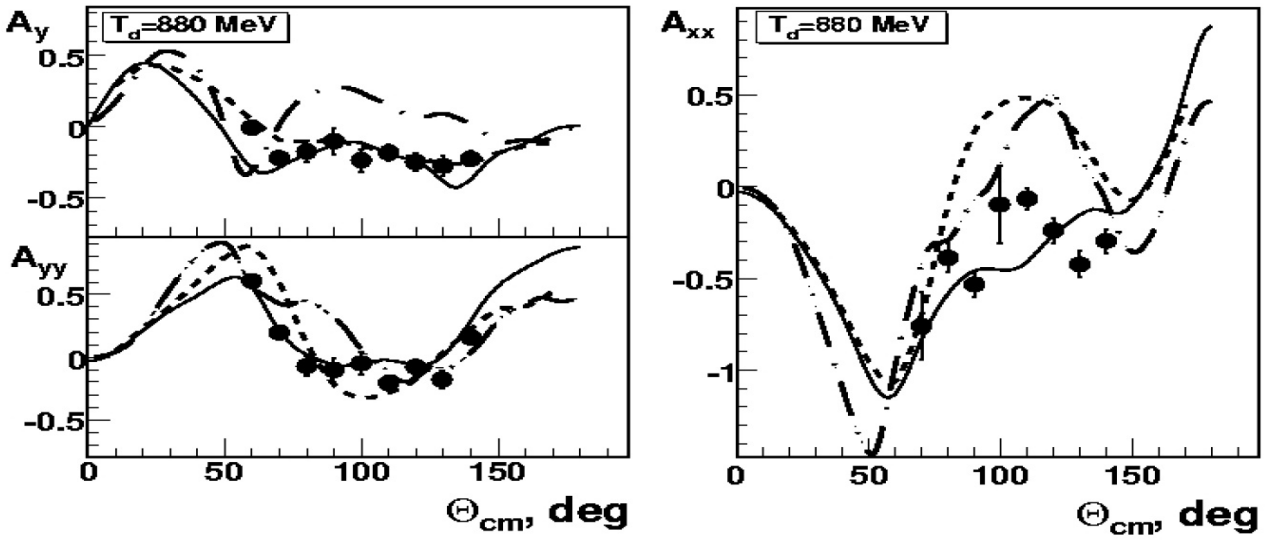
Internal Target Station is very well suited for the measurements of the deuteron- induced reactions observables at large scattering angles.

Setup to study dp- elastic scattering at ITS at Nuclotron in 2005



- **Deuterons and protons in coincidences using scintillation counters**
- **Internal beam and thin CH_2 target (C for background estimation)**
- **Polarization measurement at 270 MeV**
- **Analyzing powers measurement at 880 and 2000 MeV**
- **The data were taken for three spin modes of PIS: unpolarized, "2-6" and "3-5" $(p_z,p_{zz}) = (0,0)$, (1/3,1) and (1/3,-1)**

Analyzing powers in dp- elastic scattering at 880 MeV



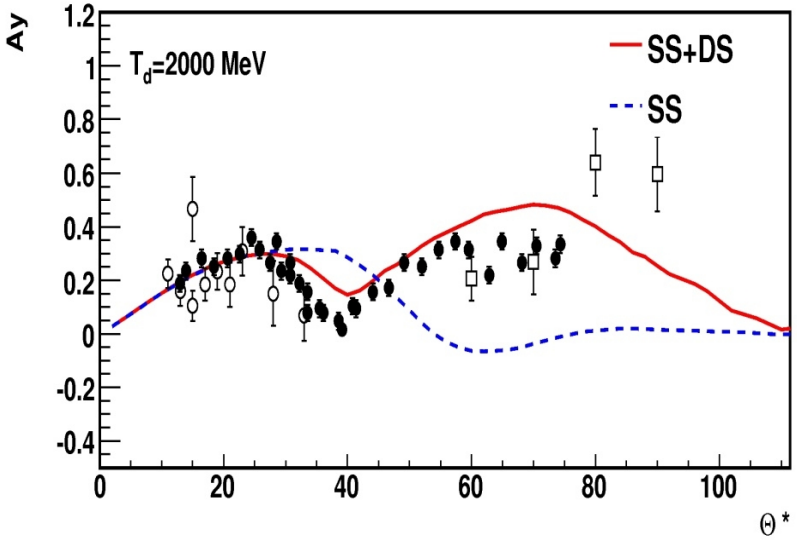
Dashed lines are the multiple scattering model calculations using CD -Bonn DWF (N.B.Ladygina, Phys.Atom.Nucl.71 (2008) 2039)

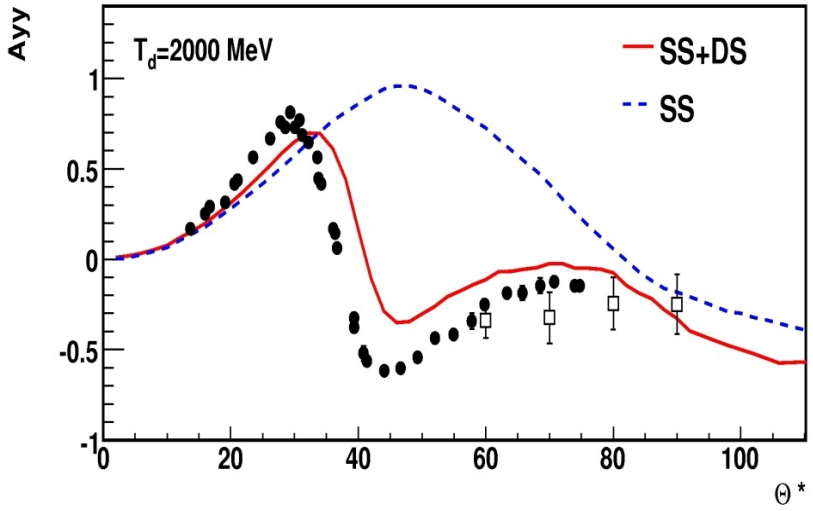
Solid lines are the Faddeev calculations using CD-Bonn potential (H.Witala, private communication)

Dott-dashed lines are the optical-potential calculations using Dibaryon DWF (M.Shikhalev, Phys.Atom.Nucl.72 (2009) 588)

Published in P.K.Kurilkin et al., Phys.Lett.B715 (2012) 61-65

A_y and A_{yy} in dp- elastic scattering at 2000 MeV



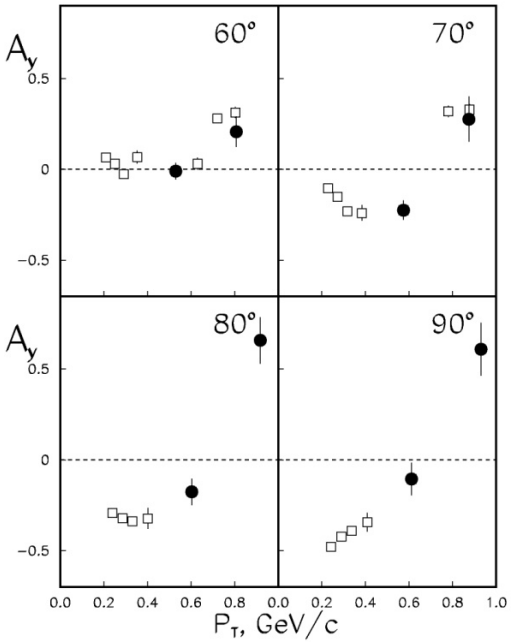


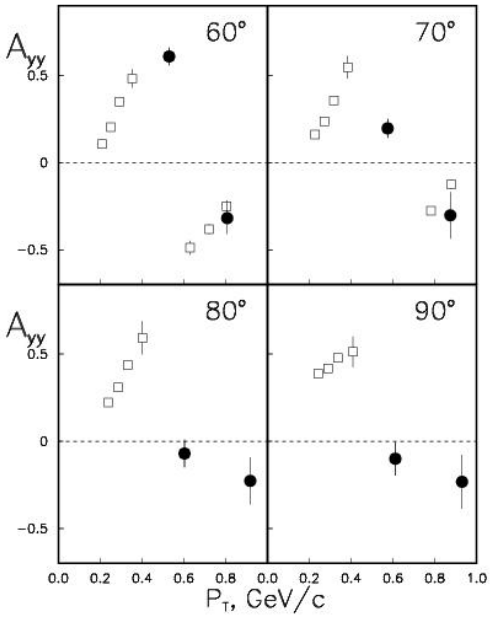
Open squares are the data obtained at Nuclotron JINR.
Open circles are the Synchrophasotron data (V.V.Glagolev, Eur. Phys. J. A48 (2012) 182)

Solid symbols are the data obtained by ANL group (Haji-Saied et al., Phys.Rev.C.36 (1987) 2010).

Dashed and solid lines are the relativistic multiple scattering model calculations using CD- Bonn DWF taking into account single scattering and single+double scattering, respectively.

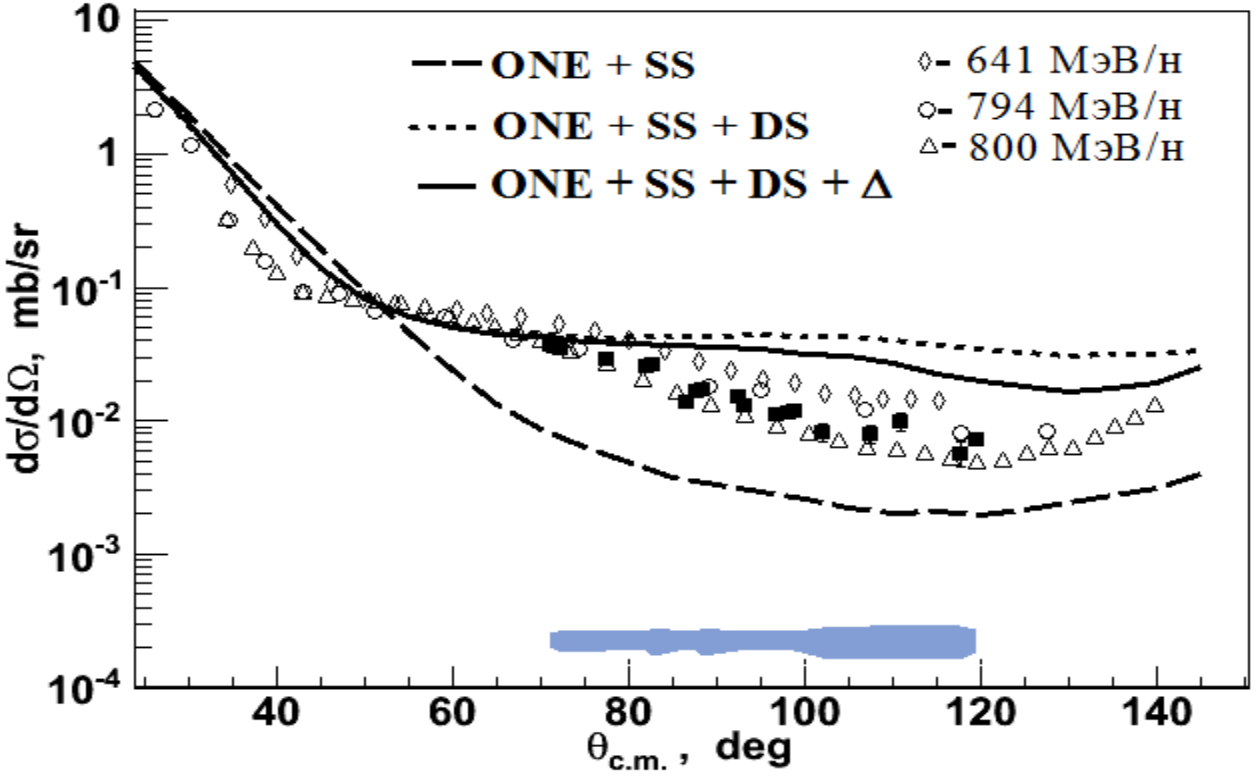
Energy dependence of the dp-elastic scattering analyzing powers at fixed scattering angles in the c.m.s.





- **Full symbols are the data obtained at JINR**
- **Open symbols are the data obtained at RIKEN, Saclay and ANL**
- **The study of the energy dependence of the analyzing powers in dp- elastic scattering at large p_T is one of the tools to study spin effects in cold dense matter**

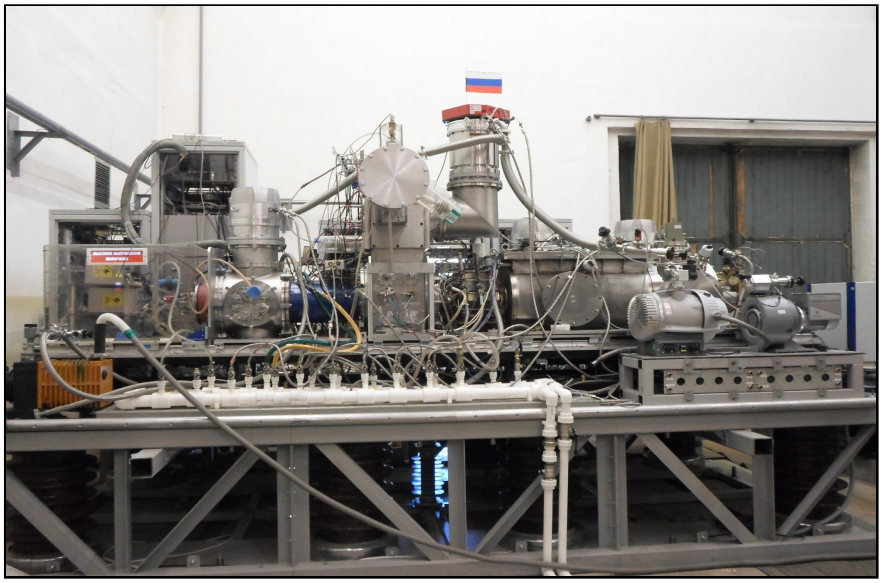
dp- elastic scattering cross section at 1400 MeV



A.A.Terekhin et al., JINR Preprint P1-2017-33 (2017),
to be published in Phys.Atom.Nucl. (2017).

Relativistic multiple scattering model calculation:
N.B.Ladygina, Eur.Phys.J, A52 (2016) 199

New Source of Polarized Ions



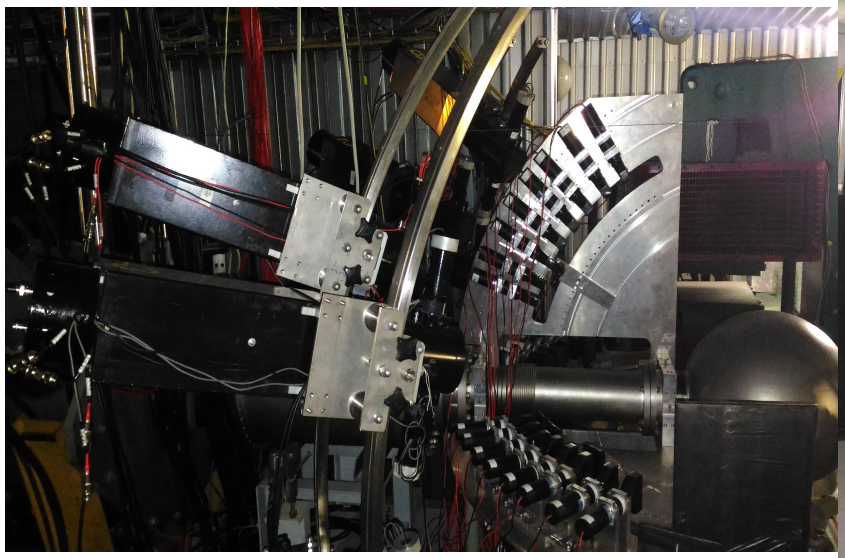
New source will provide up to $2*10^{10}$ ppp and higher values of polarization than **POLARIS**.

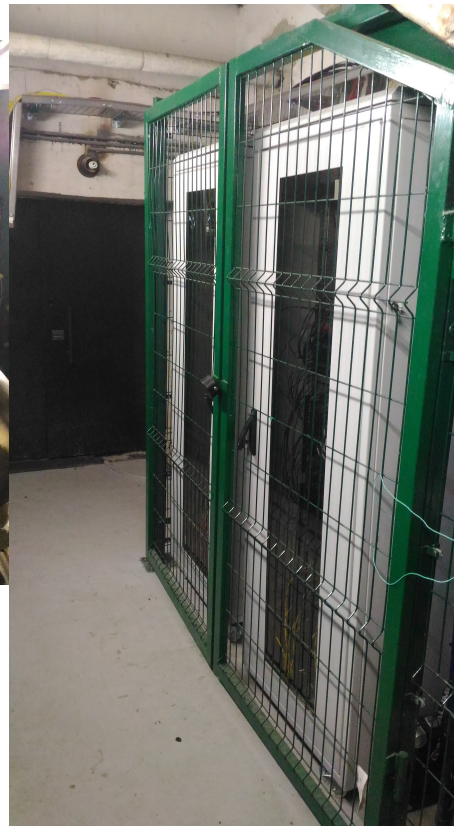
Part of the **IUCF** source was used for the construction. The putting into operation of new SPI was in 2016.

Large variety of the spin modes. For instance, **DSS** project would like to use the spin modes with the following ideal values of (p_z, p_{zz}): (0,0), (0,-2), (+1,+1) and (-1,+1).

Figure of merit will increase by a factor ~ 10^3

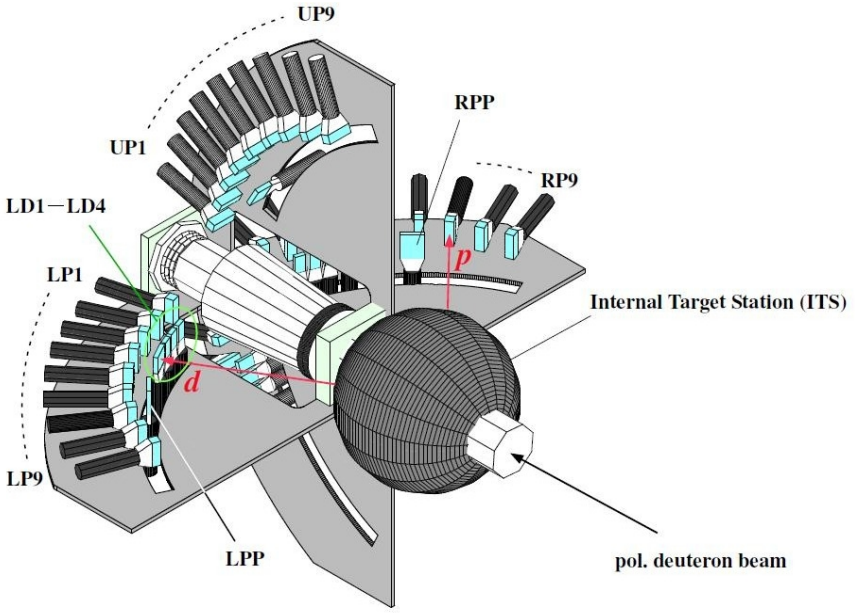
Upgrade of the Delta-LNS (DSS) setup at ITS at Nuclotron

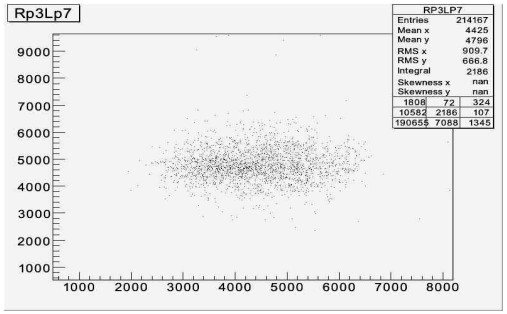




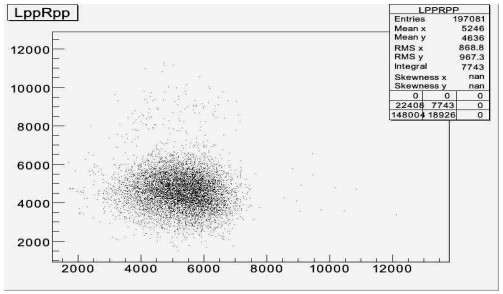
New infrastructure, cabling
New HV system (Mpod)
New VME DAQ
40 counters for dp-elastic scattering studies
8 dE-E detectors for dp -breakup studies

Results from the commissioning run at Nuclotron at 270 MeV (June 2016)





DP

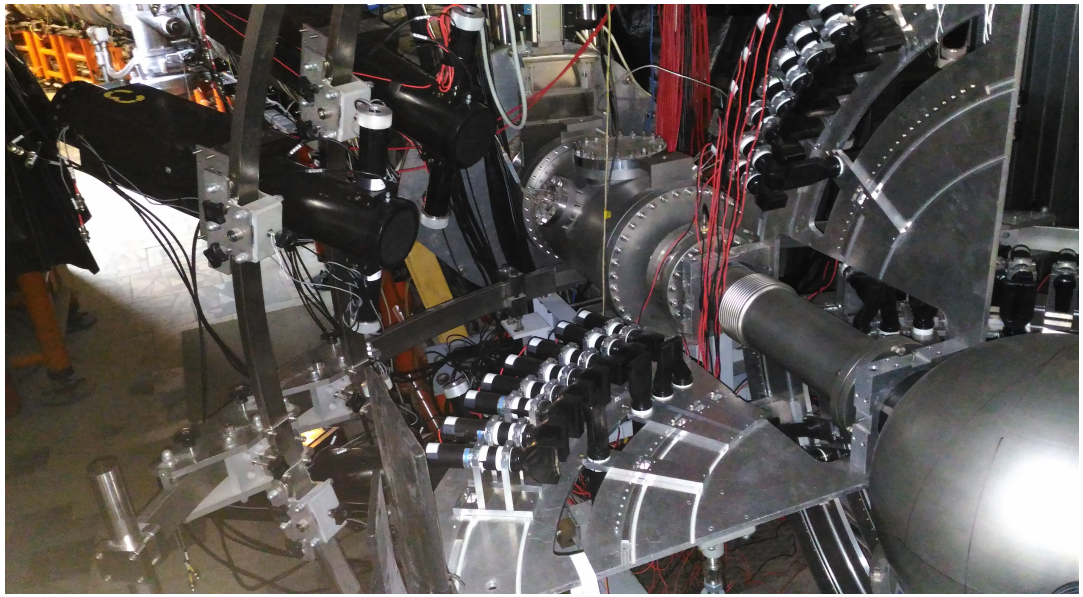


PP

- Deuterons and protons in coincidences using scintillation counters
- Internal beam and thin CH_2 target (C for background estimation)
- Measurements at 270 MeV

- The setup was ready to take the polarized data.

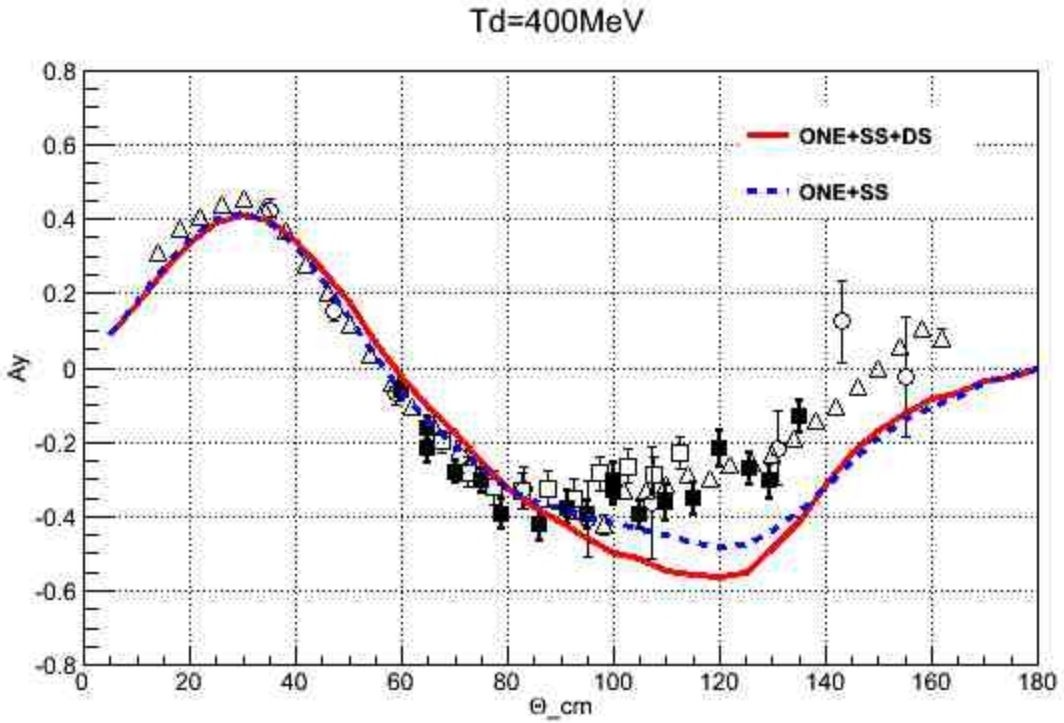
Setup to study dp- elastic scattering at ITS at Nuclotron in 2016-2017.



- **Deuterons and protons in coincidences using scintillation counters**
- **Internal beam and thin CH_2 target (C for background estimation)**
- **Permanent polarization measurement at 270 MeV (between each energy).**
- **Analyzing powers measurement at 400-1800 MeV**
- **The data were taken for three spin modes of SPI: unpolarized, "2-6" and "3-5" $(p_z,p_{zz}) = (0,0)$, (1/3,1) and (1/3,-1).**
- **Typical values of the polarization was 70-75% from the ideal values.**

(talk of Ya.Skhomenko).

Angular dependence of the vector analyzing power Ay in dp-elastic scattering at 400 MeV

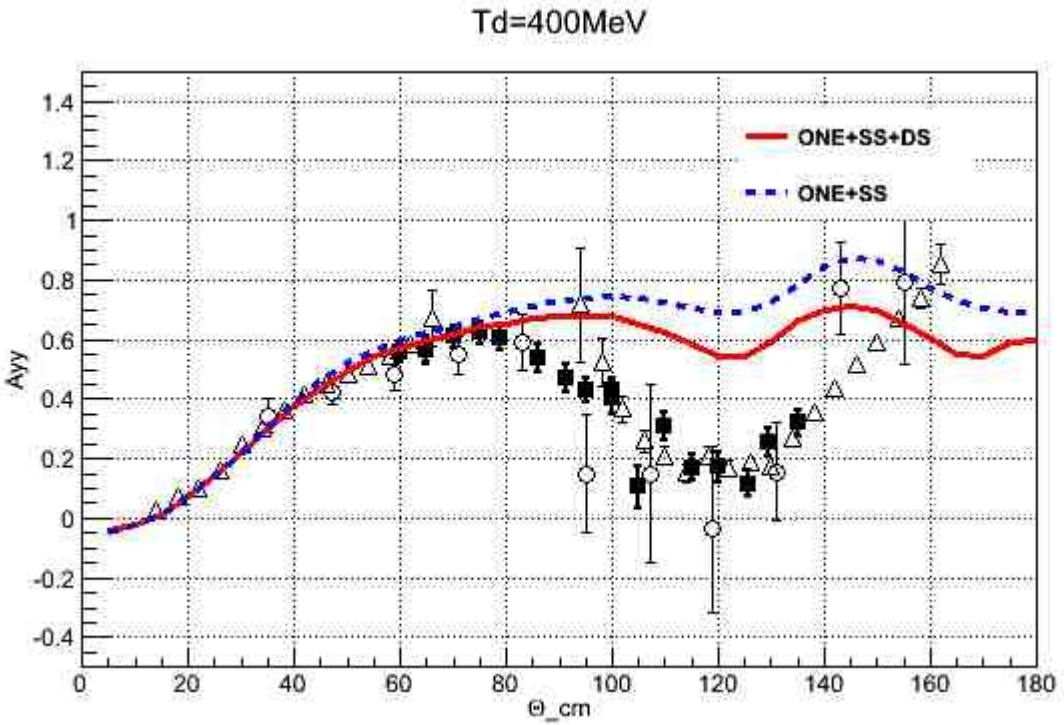


Full squares are the data fom Nuclotron (December 2016)

Curves are the relativistic multiple sacttering model calculations

N.B.Ladygina, Eur.Phys.J, A42 (2009) 91

Angular dependence of the tensor analyzing power Ayy in dp-elastic scattering at 400 MeV

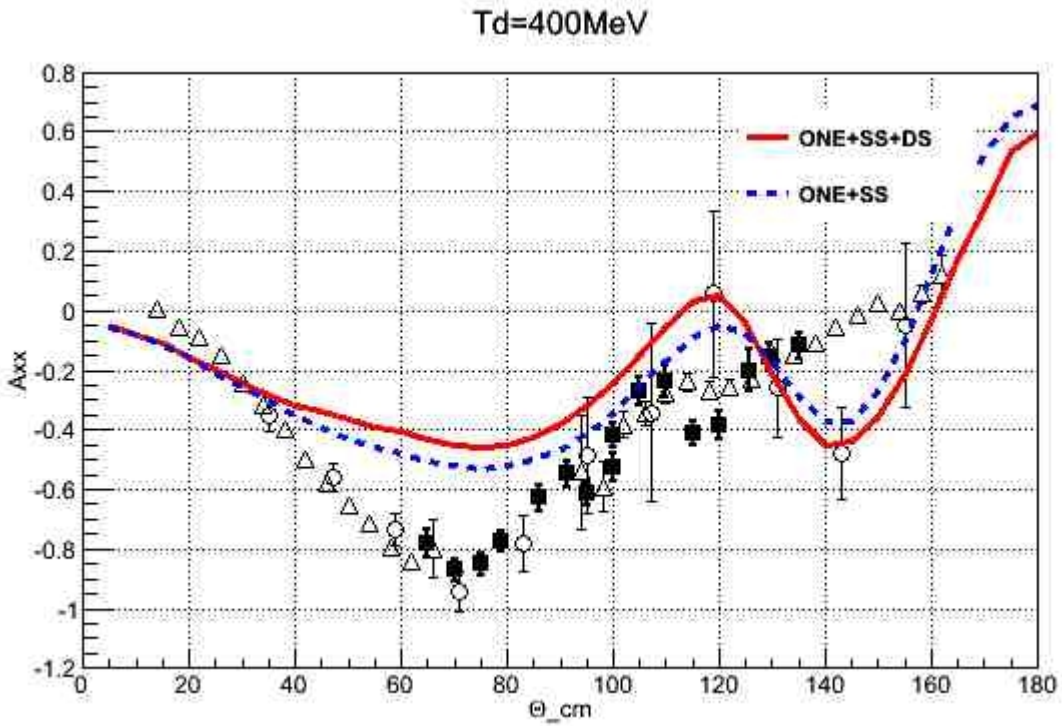


Full squares are the data fom Nuclotron (December 2016)

Curves are the relativistic multiple sacttering model calculations

N.B.Ladygina, Eur.Phys.J, A42 (2009) 91

Angular dependence of the tensor analyzing power Axx in dp-elastic scattering at 400 MeV

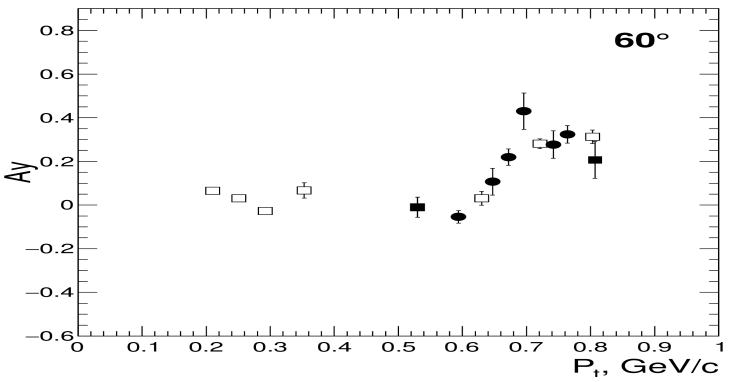


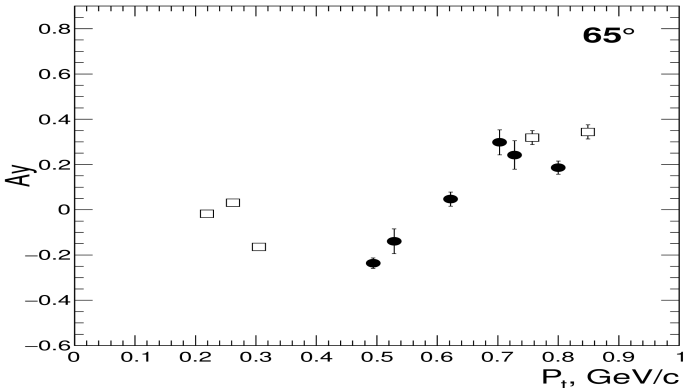
Full squares are the data fom Nuclotron (December 2016)

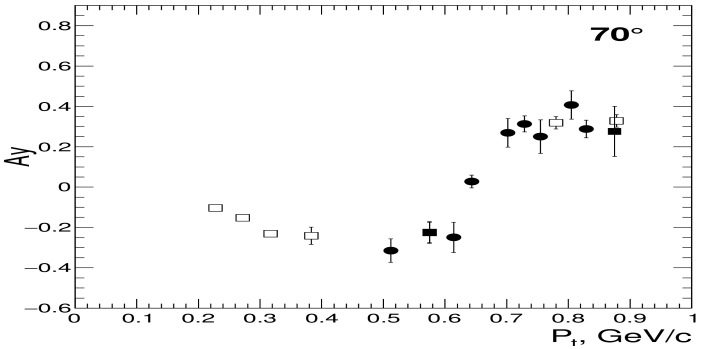
Curves are the relativistic multiple sacttering model calculations

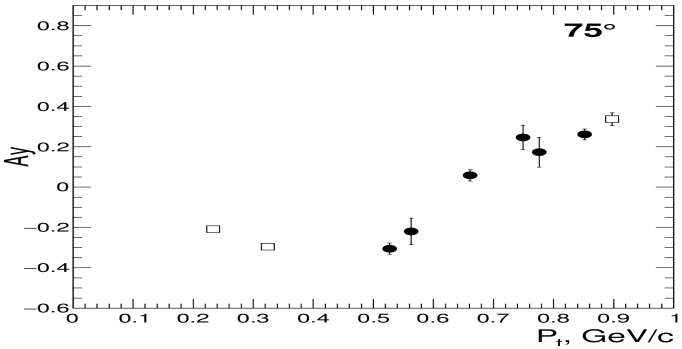
N.B.Ladygina, Eur.Phys.J, A42 (2009) 91

Energy dependence of the vector analyzing power Ay in dp-elastic scattering at 700-1800 MeV



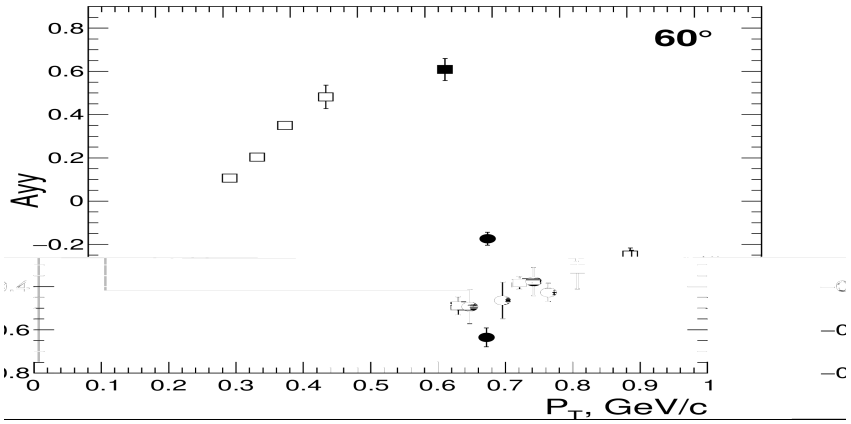


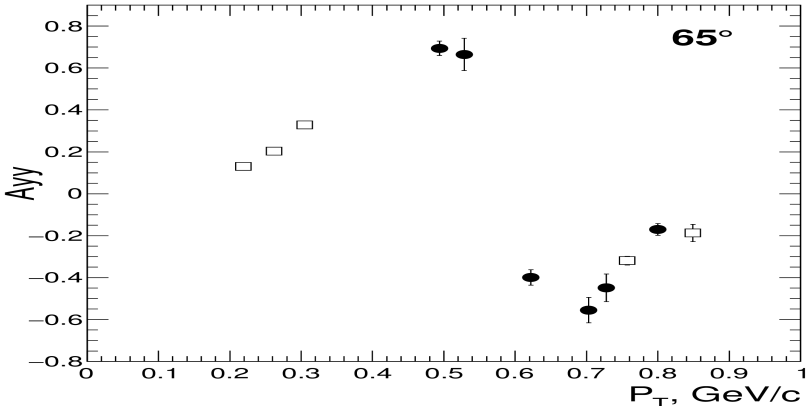


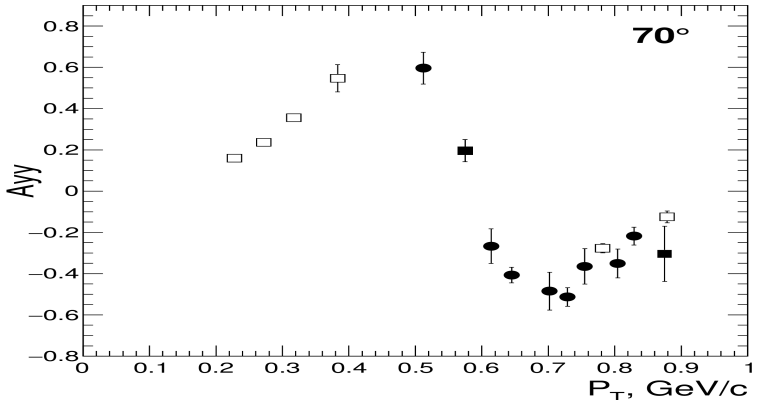


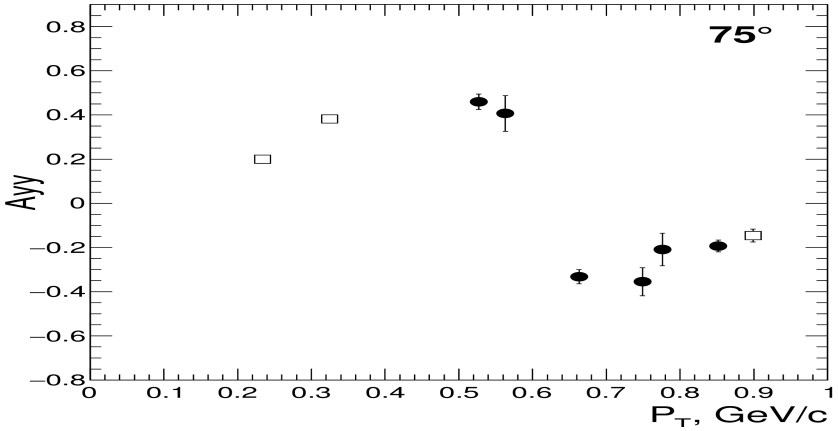
Full circles are the new preliminary data fom Nuclotron (2016-2017).
Full squares are the data fom Nuclotron (2005).
Open symbols are the world data.

Energy dependence of the tensor analyzing power Ayy in dp-elastic scattering at 700-1800 MeV



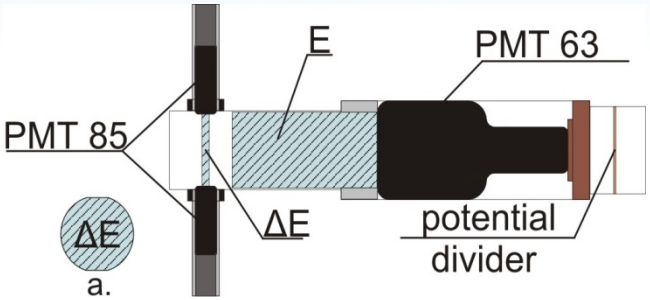


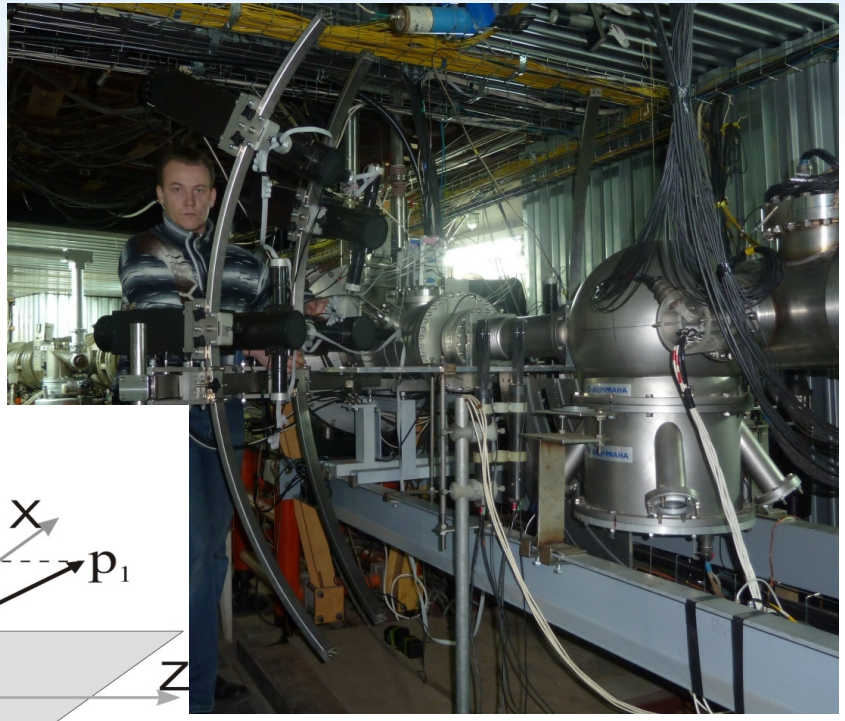




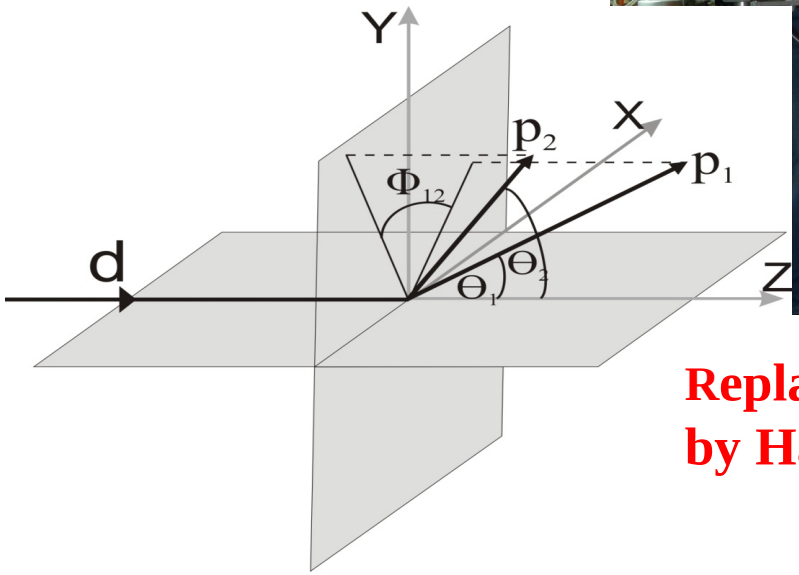
Full circles are the new preliminary data fom Nuclotron (2016-2017).
Full squares are the data fom Nuclotron (2005).
Open symbols are the world data.

Experimental setup for dp-breakup.



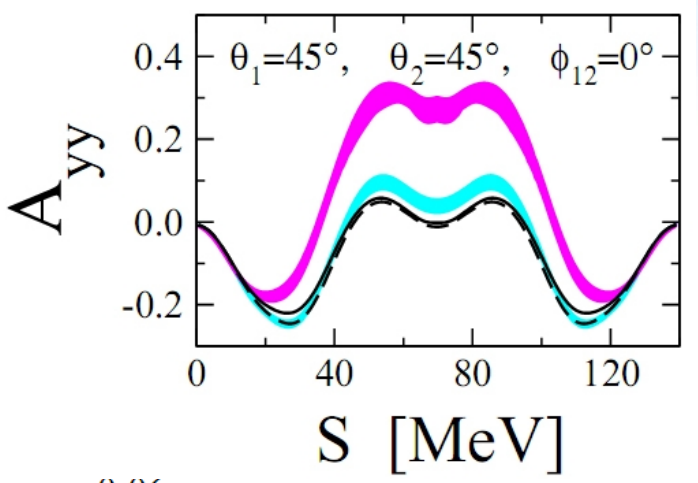


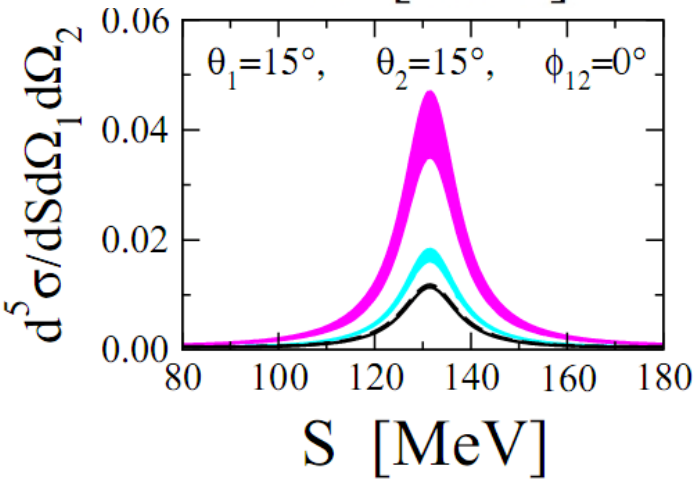
Θ (12°, 45°)
Φ (0°, 360°)
Space angle of
the detector 4.6°.



Replace of the PMTs 85 and 63 by Hamamatsu PMTs

dp breakup reaction.





This slide presents tensor analyzing power Ayy (top) and differential cross section in selected breakup configurations at 200 MeV (bottom).

- **The light shaded band (blue) contains the theoretical predictions based on CD-Bonn, AV18, Nijm I, II and Nijm 93.**
- **The darker band (magenta) represents predictions when these NN forces are combined with the TM 3NF.**
- **The solid line is for AV18+Urbana IX and the dashed line for CD Bonn+TM**

One can see that the inclusion of 3NF have great impact on the values of analyzing power and cross section.

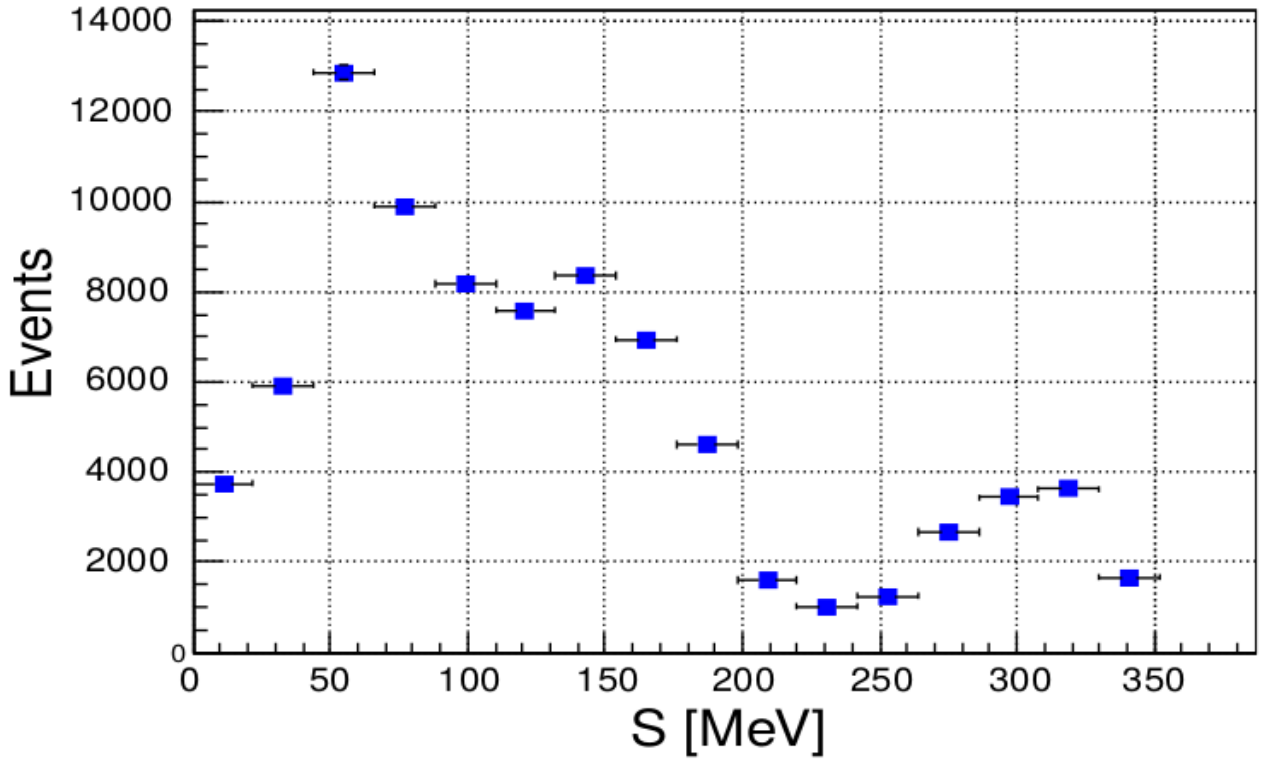
Θ_1 – polar angle of the 1-st proton.

Θ_2 – polar angle of the 2-nd proton.

S – arc length along the kinematical curve.

Φ_{12} – azimuth angle with respect to the horizontal plane.

Dp breakup reaction at 400 MeV, θ_{p1}= 39º(±2.3º), θ_{p2}=43º(±2.3º)

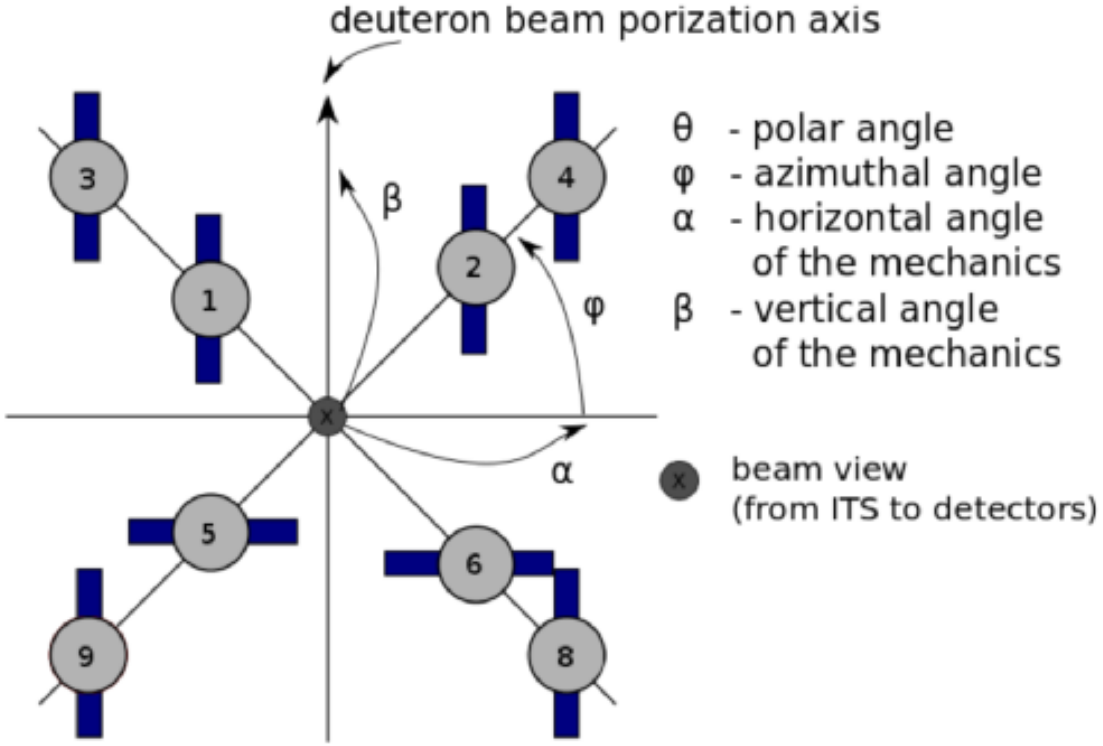


dp → ppn, two protons registered at angles:

θ_{p1}= 39º (±2.3º), θ_{p2}=43º (±2.3º)

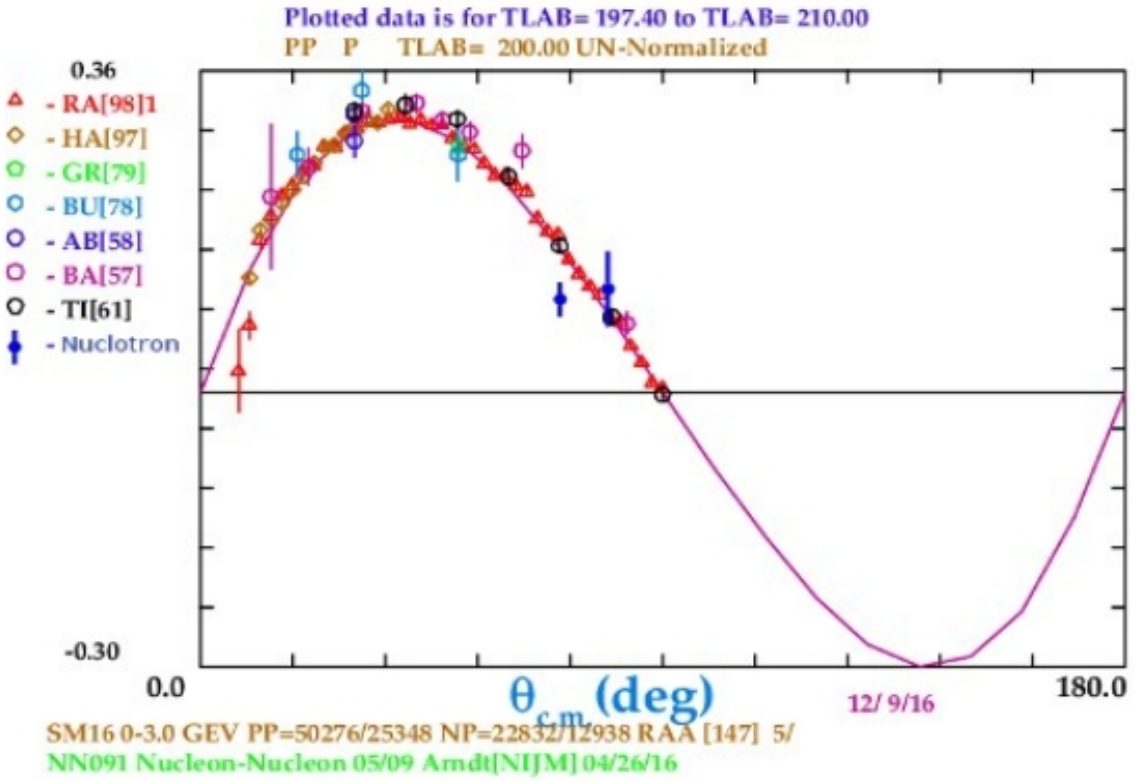
one Arm is fixed at 43º, 2nd moving (27º,31º,35º,39º,43º)

dp breakup reaction, polarized beam



Detector placement is determined by polar **θ** and azimuthal **φ** angles.
Azimuthal angle **φ** have anticlockwise direction.
Detector setup for the case of analyzing power investigation.

AP of dp breakup reaction at 400 MeV, pp-quasi elastic data



(pz, pzz)
=
(-1/3, 1)
(-1/3, -1)

Angular dependence of the vector analyzing power $\mathbf{iT}_{11}$ at energy of **200** MeV/n. Data obtained at Nuclotron JINR are represented by full blue symbols (72.3° and 76.5° in cm). Other symbols - world data.

dp breakup reaction at 400 MeV, analyzing power data

Spherical analyzing powers iT_{11} and T_{20}. Detector configuration is determined by polar θ_1 and θ_2, and azimuthal angles φ. Azimuthal angle is related to the angle of the detector which is closest to beam direction.

pp -quasi elastic
72.3° and 76.5°

Conf.	θ_1 [°]	θ_2 [°]	φ [°]	iT_{11}	T_{20}	iT_{11} combined	T_{20} combined
detectors – 5, 4	34.8	52.5	135	0.10 ± 0.02	0	-	-
detectors – 6, 3	36.8	50.4	45	0.11 ± 0.06	0	-	-
detectors – 1, 6	34.8	36.8	135	0.55 ± 0.15	0.13 ± 0.30	0.47 ± 0.10	0.02 ± 0.20
detectors – 5, 2	34.8	36.8	135	0.39 ± 0.13	-0.09 ± 0.27		

Results combined

Further DSS plans

Final analysis of the systematic data on the cross section and analyzing powers A_y, A_{yy} and A_{xx} in dp- elastic scattering between 270 MeV and 2000 MeV at ITS.

Preparation of the experiments on the systematic studies of the analyzing powers A_y, A_{yy} and A_{xx} in dp- elastic scattering between 270 MeV and 700 MeV using new SPI at Nuclotron to study the manifesttion of the short-range 3NFs.

Preparation for the taking of new polarized data for the dp (pd)- nonmesonic breakup at the energies between 300 and 500 MeV for different kinematic configurations at ITS with polarized beams.

Preparation of the experiment on the energy scan of the nucleon analyzing power A_y^p in pd- elastic scattering between 135 MeV and 1000 MeV at ITS.

Preparation of the experiments with extracted polarized deuteron beam (SS of SRC - see Proceedings of IBSHEPP-XXII, SPIN-2014 and DSPIN15).

Conclusion

Upgraded Nuclotron with new SPI provides quite unique opportunity for the studies of the spin effects and polarization phenomena in few body systems.

The realization of the DSS program at ITS will allow to obtain the crucial data on the spin structure of 2-nucleon and 3- nucleon short range correlations.

The first natural step in these studies, namely, the energy scan of the deuteron analyzing powers in dp- elastic scattering has been performed in 2016-2017.

Next experiments using polarized deuterons and protons at ITS are in preparation (SR 3NF and S3RC).

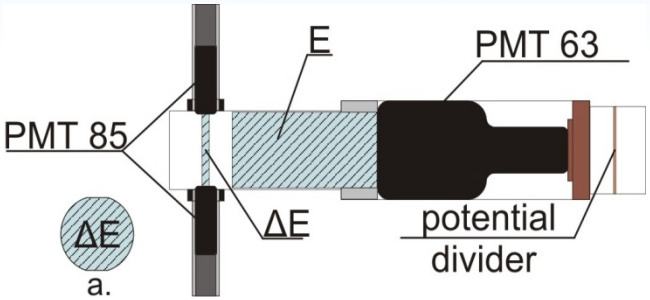
The extention of the studies to the high energies is possible with the extracted polarized deuteron and proton beams.

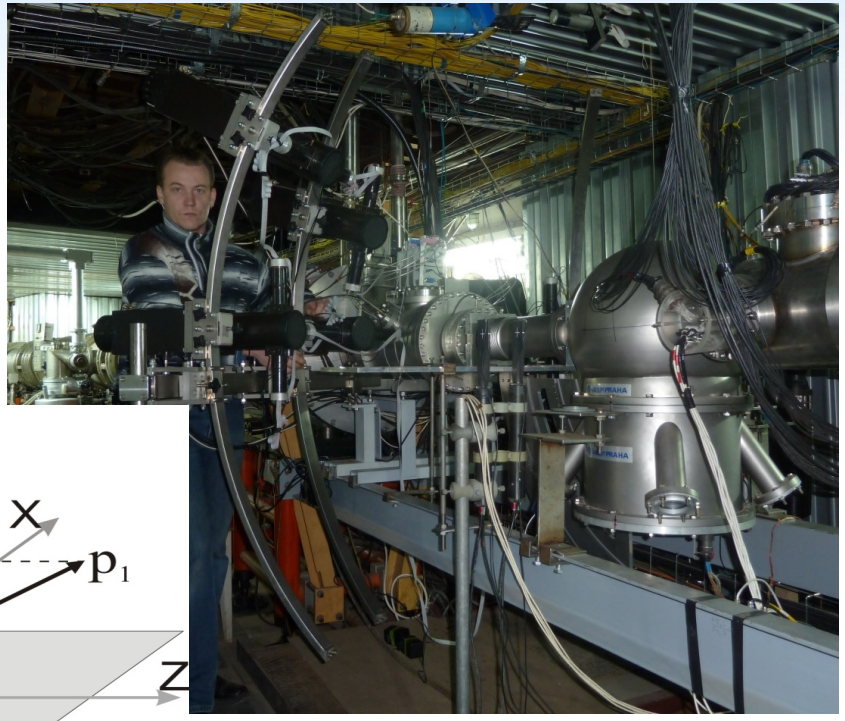
Thank you for the attention!

Our work is dedicated to the memory of L.S.Zolin

Professor Leonid Zolin for many years was one of the leading scientists in the field of polarization phenomena in nuclear reactions at relativistic energies and in the development of the deuteron beam polarimetry at JINR (Synchrophasotron-Nuclotron).

Experimental setup for dp-breakup.





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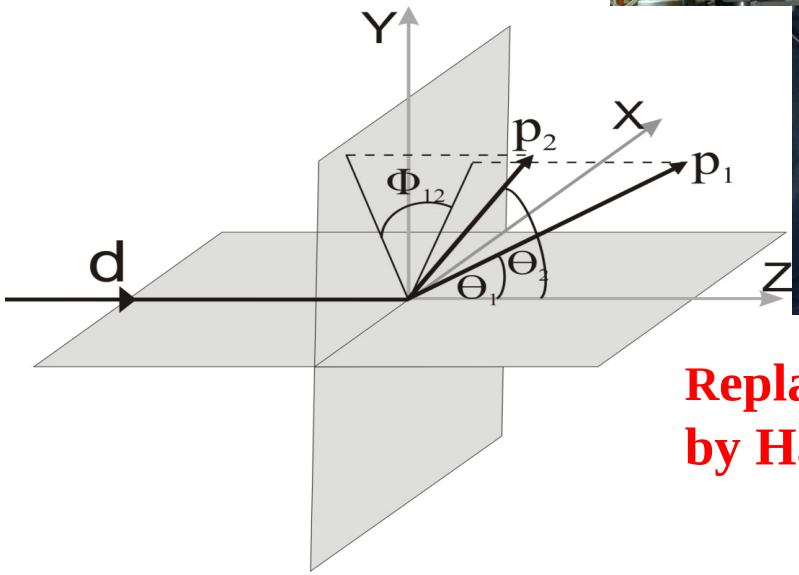

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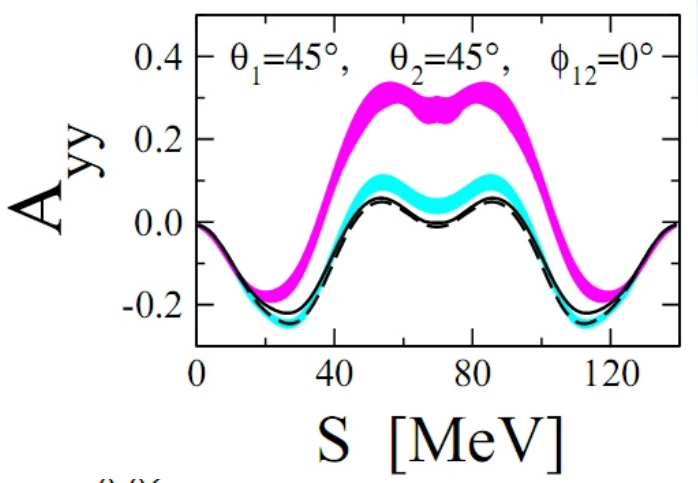

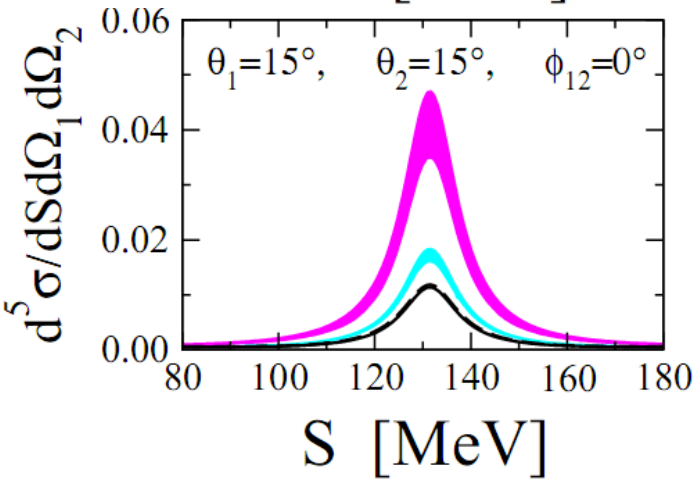

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S – arc length along the kinematical curve.

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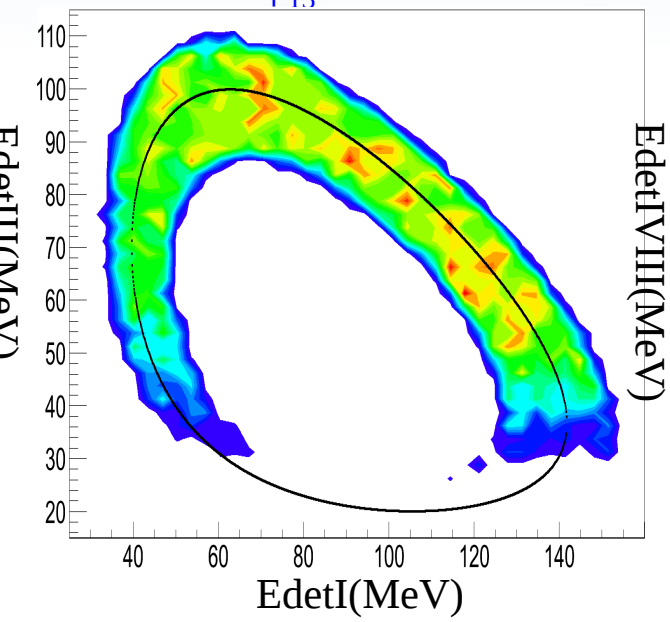
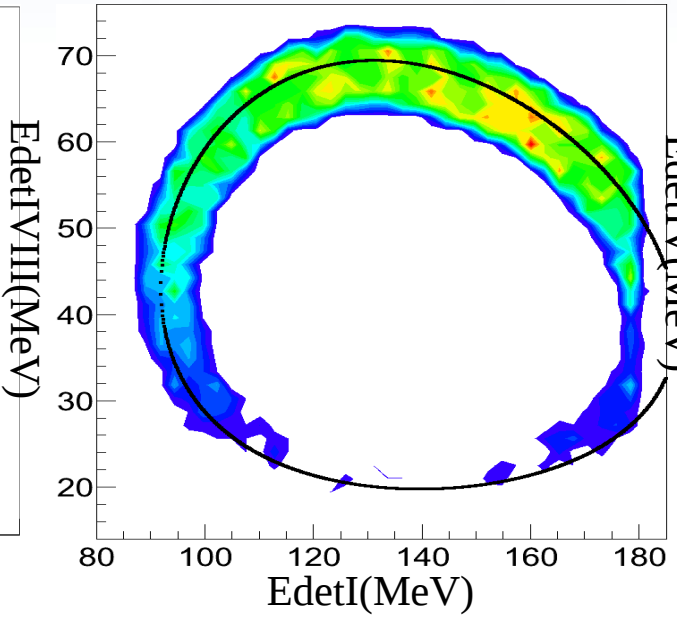
The deuteron energy of 400 MeV.

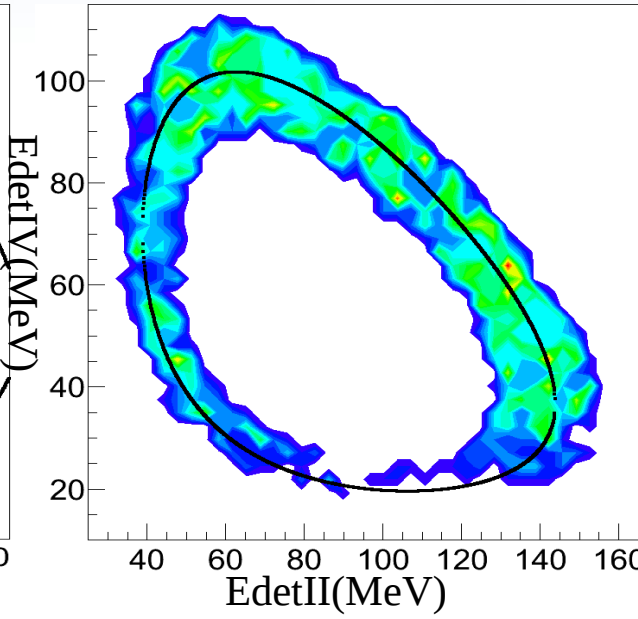
$\Theta_1 = 25^0$, $\Theta_3 = 33.7^0$, $\varphi_{13} = 44.6^0$



$\Theta_1 = 25.2^0$, $\Theta_8 = 53.6^0$, $\varphi_{18} = 135.5^0$



$\Theta_2 = 25^0$, $\Theta_4 = 33.7^0$, $\varphi_{24} = 46.5^0$



Correlations of the proton energies with the cut on missing mass (940MeV±10MeV) of deuteron energy 400 MeV.

Conclusion

Upgraded Nuclotron with new PIS could provide quite unique opportunity for the studies of the spin effects and polarization phenomena in few body systems.

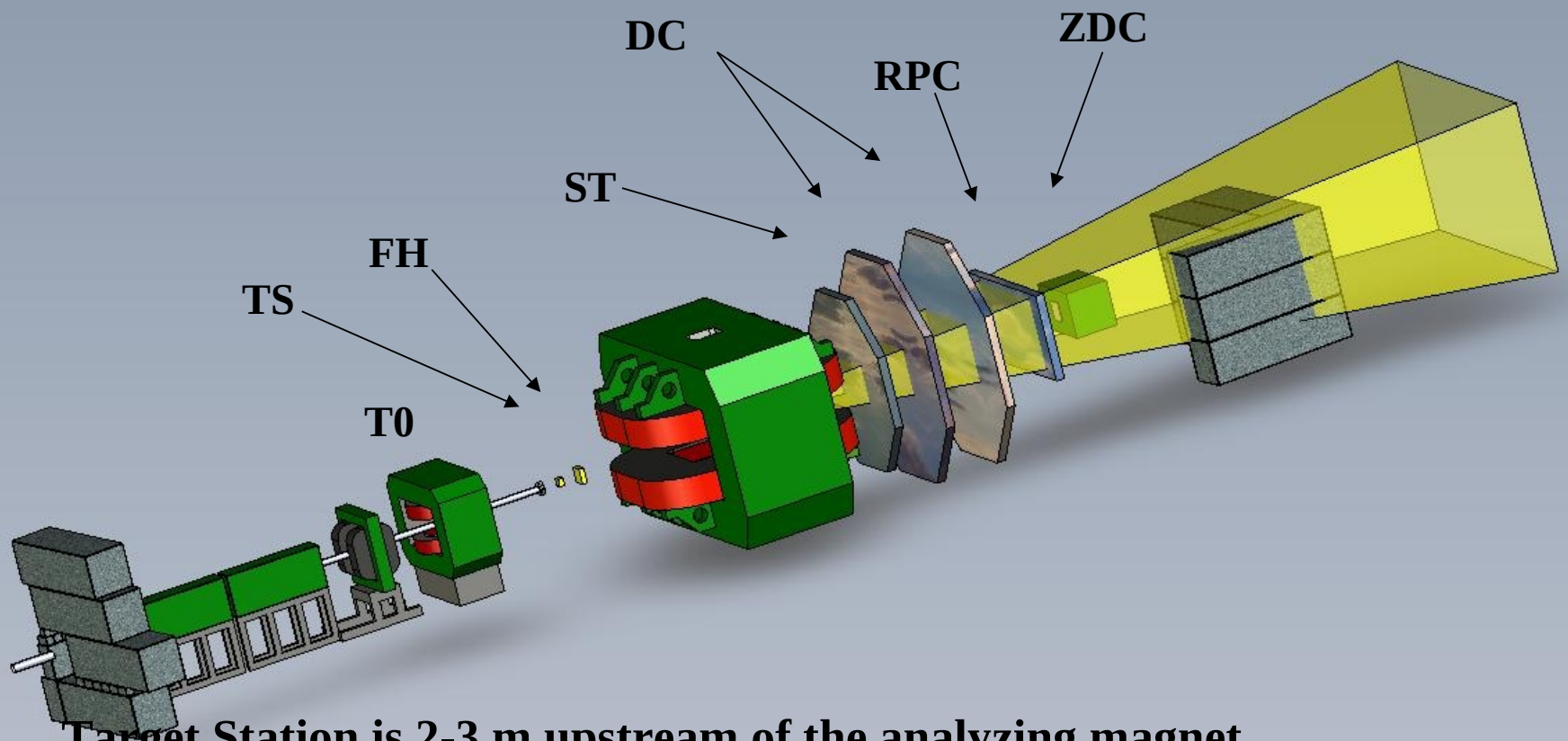
The realization of the DSS program at ITS will allow to obtain the crucial data on the spin structure of 2-nucleon and 3- nucleon short range correlations.

The first natural step in these studies is the energy scan of the deuteron analyzing powers in dp- elastic scattering.

The extent of the studies to the high energies is possible with the extracted polarized deuteron beam (for example with the BM@N setup).

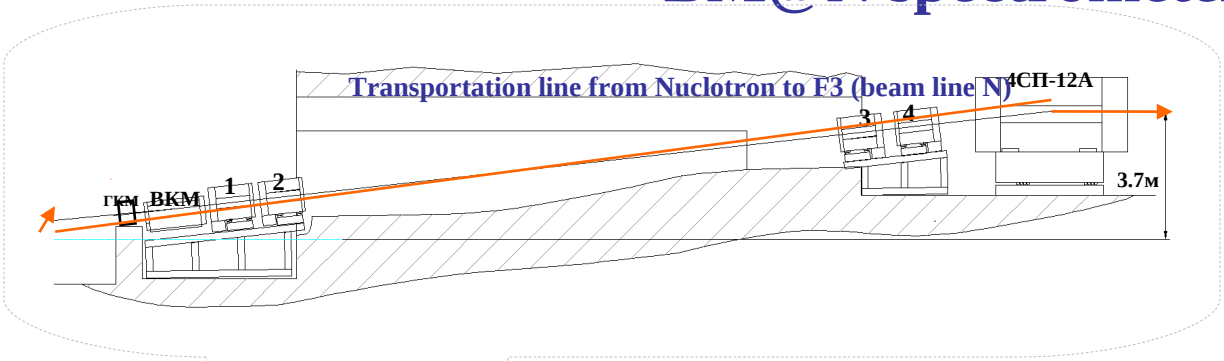
Thank you for the attention!

Stage 1 of BM@N setup for spin studies



Target Station is 2-3 m upstream of the analyzing magnet
RPC at the distance of 8-10 m from the target
Forward (FH) or part of Inner (GEMs or STS) and Outer (DC) trackers are neccessary

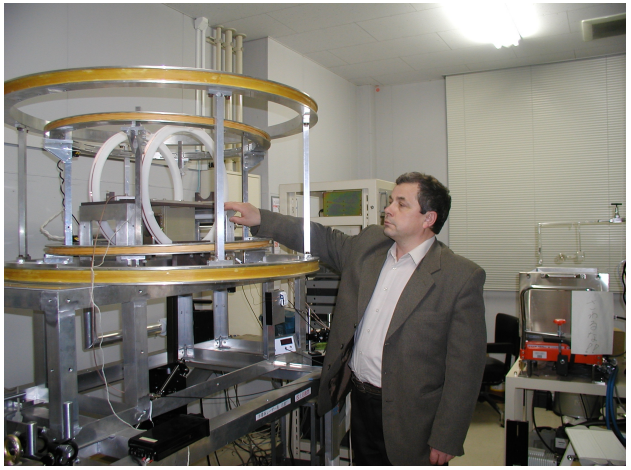
Transportation line of the Nuclotron extracted beam to the BM@N spectrometer



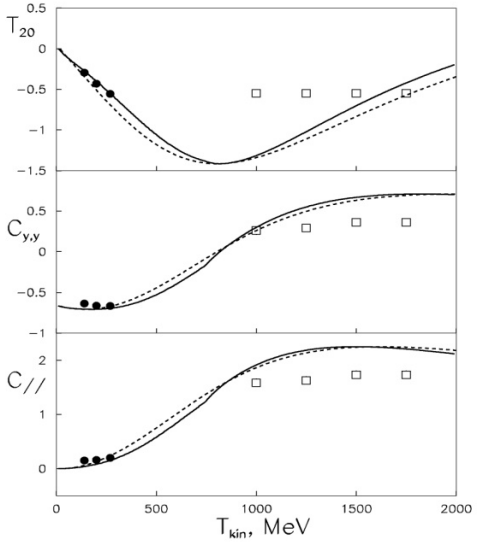
Spin physics with BM@N can be associated with different target positions: at F5(F3), F6' and F6.

Polarization observables for polarized deuteron induced reactions

Target position is in F5



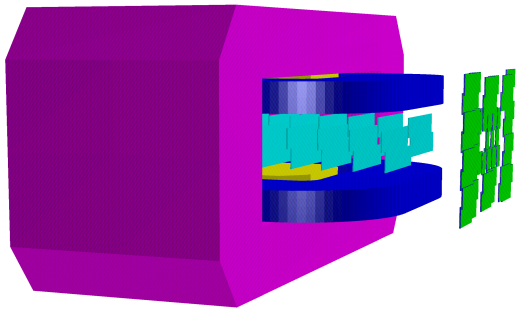
^{3}He(d,p)^{4}He



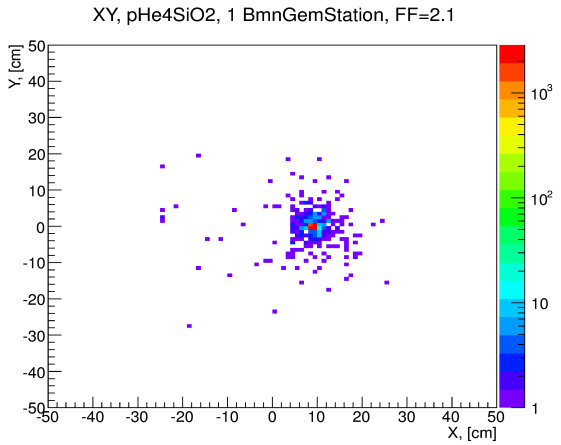
- The measurements of the tensor analyzing power T_{20} and spin correlation $C_{y,y}$ in the ^{3}He(d,p)^{4}He reaction in the kinetic energy range between 1.0 and 1.75 GeV can be performed at the BM@N area.
- The polarization observables for the p(d,p)d, d(d,p)t and d(A,p(0^o))X at intermediate and high energies also can be studied.
- Non-nucleonic degrees of freedom and baryonic resonances properties can be studied in the d(A,d(0^o))X and d(A,π^-(0^o))X reactions at different energies.
- The tensor analyzing power T_{20} can be studied for the meson production in the d(A,3He(0^o))X reactions.

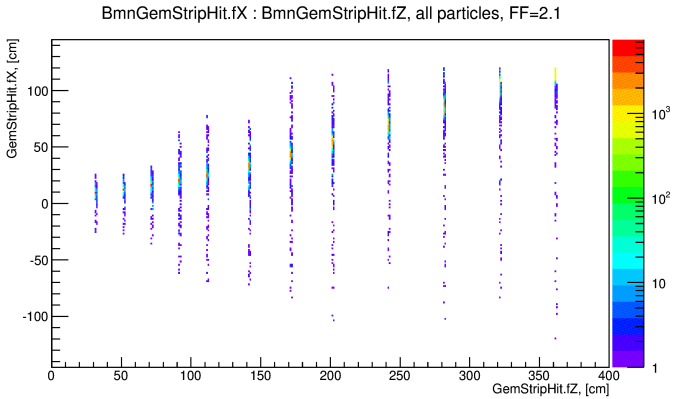
Preliminary GEANT simulation for $^{3}He(d,p)^{4}He$

BM@N GEANT model

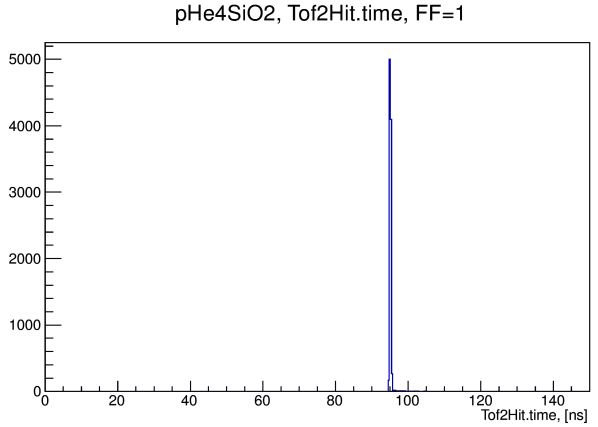


Beam profile at 1-st GEM station





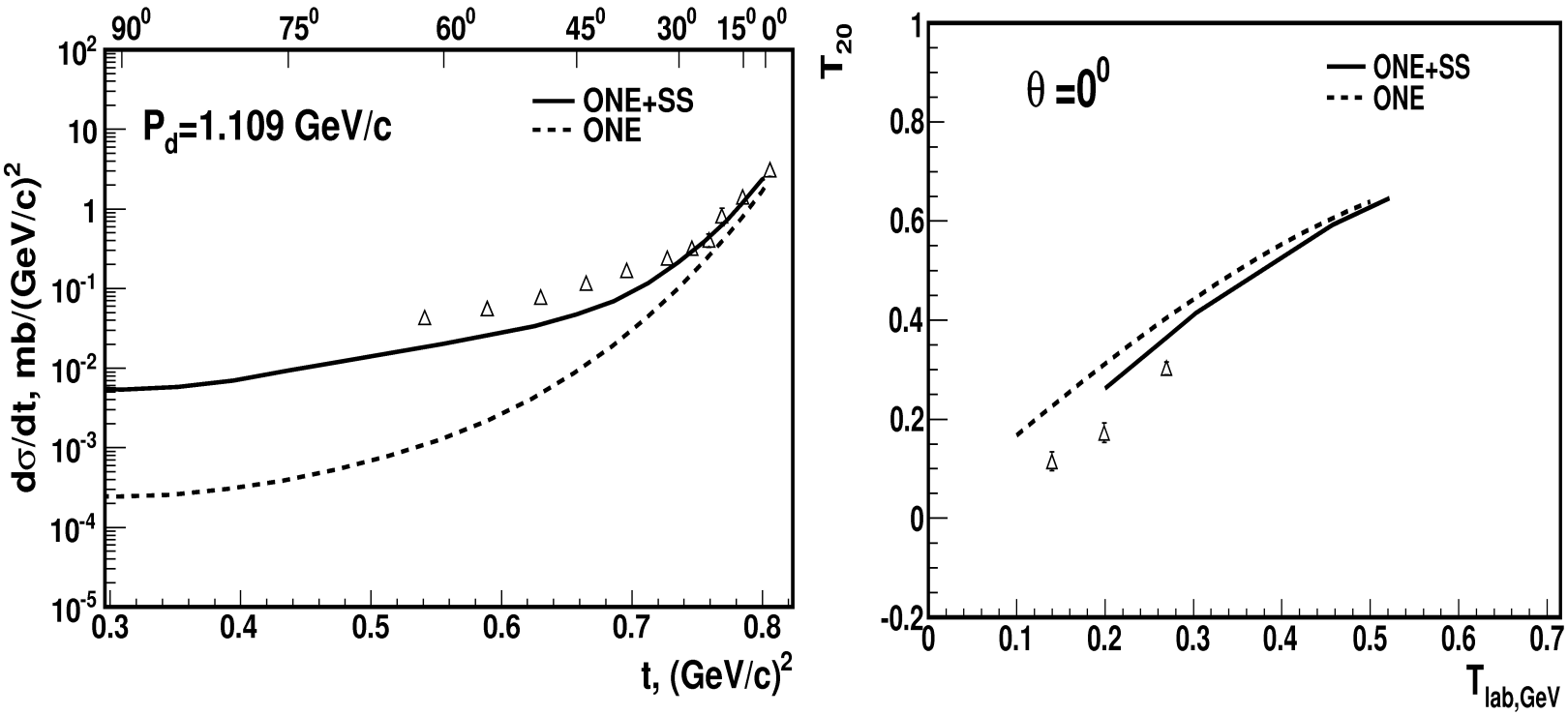
XZ profile in GEM tracker



TOF resolution for protons

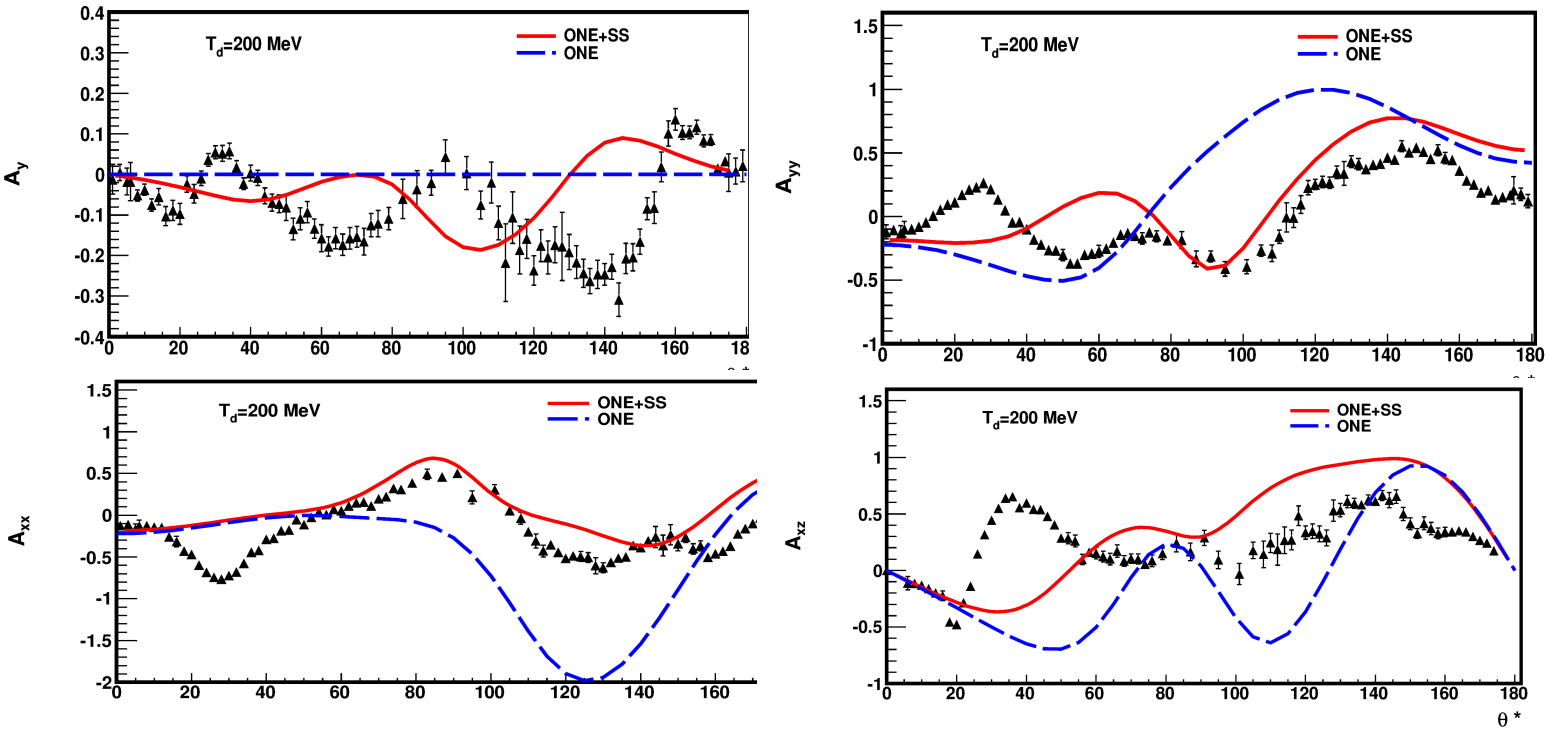
Details in the talk of M.Janek

dd → ^{3}Hen(^{3}Hp) reactions at Nuclotron energies



The relativistic multiple scattering model can be successfully used to describe the dd → ^{3}Hen(^{3}Hp) reactions in a GeV region at the Nuclotron.
The calculations require a large amount of CPUs.
The results are published in N.B.Ladygina, Few Body Systems 53 (2012) 253.

Polarization effects in the dd → ^{3}Hen(^{3}Hp) reactions at Nuclotron energies



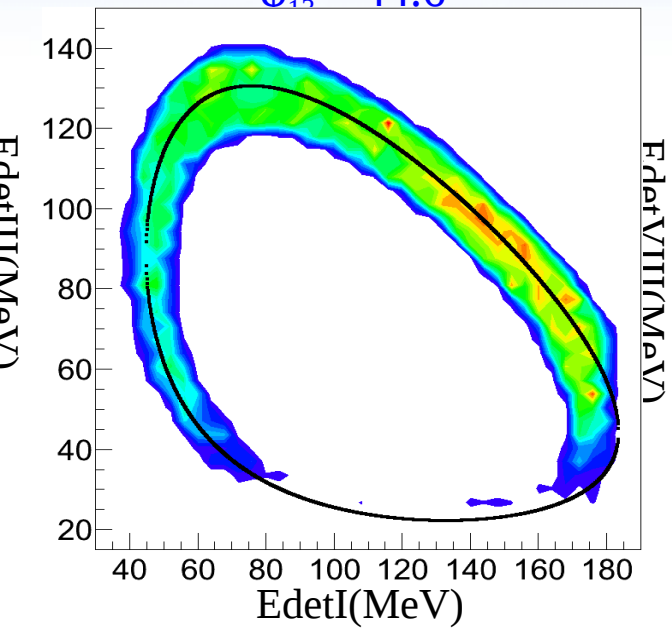
The relativistic multiple scattering model was successfully used to describe the dd → ^{3}Hen(^{3}Hp) reactions in a GeV region at the Nuclotron.
The calculations require a large amount of CPUs.
The results were published in FBS, PRC, PPN.

N.Ladygina - theory
A.Kurilkin – experiment

The deuteron energy of 500 MeV.

DSS Deuteron Spin Structure

$\Theta_1 = 24.7^0$, $\Theta_3 = 33.3^0$, $\varphi_{13} = 44.6^0$



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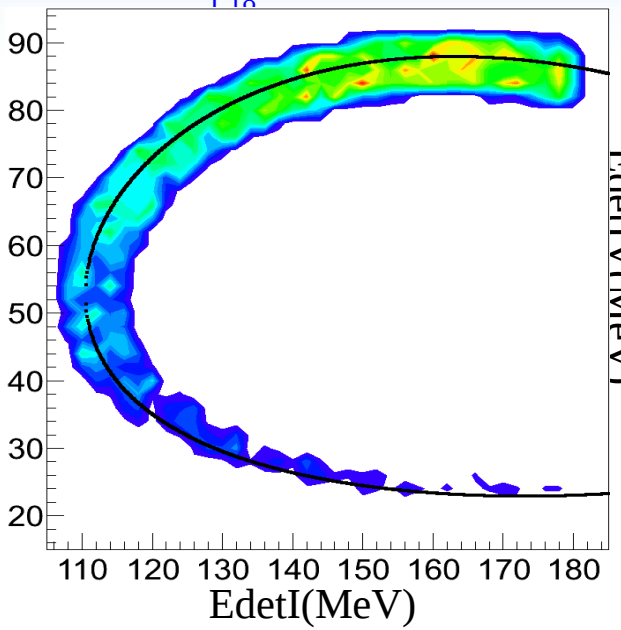

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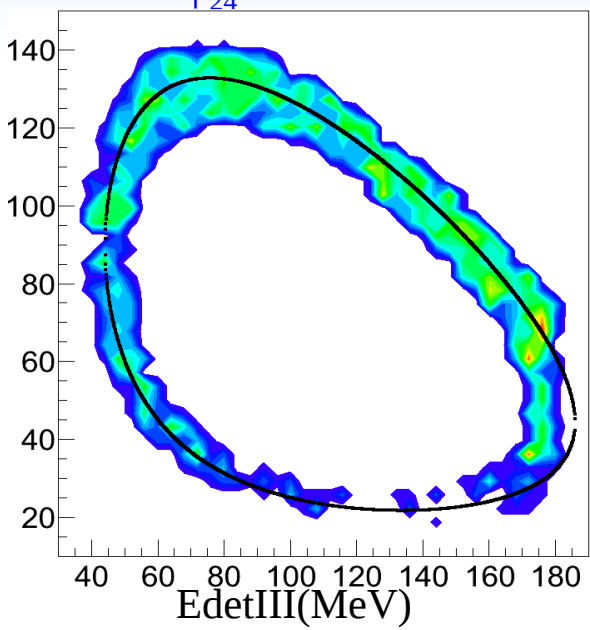
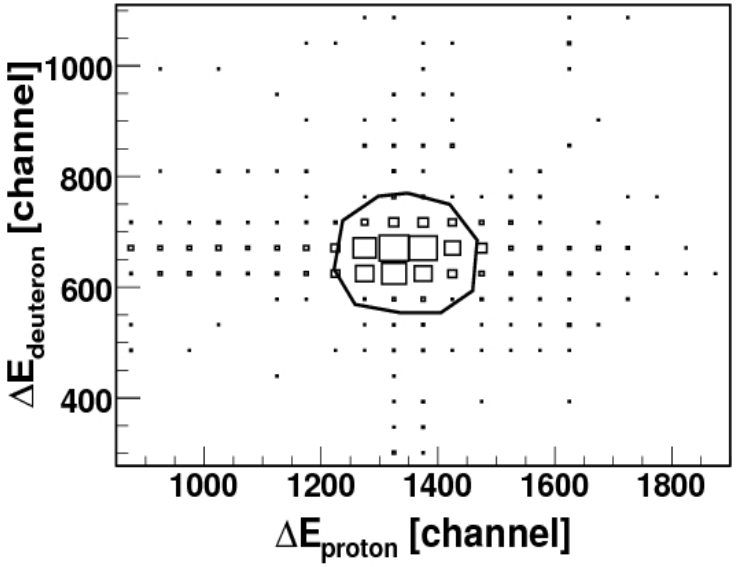


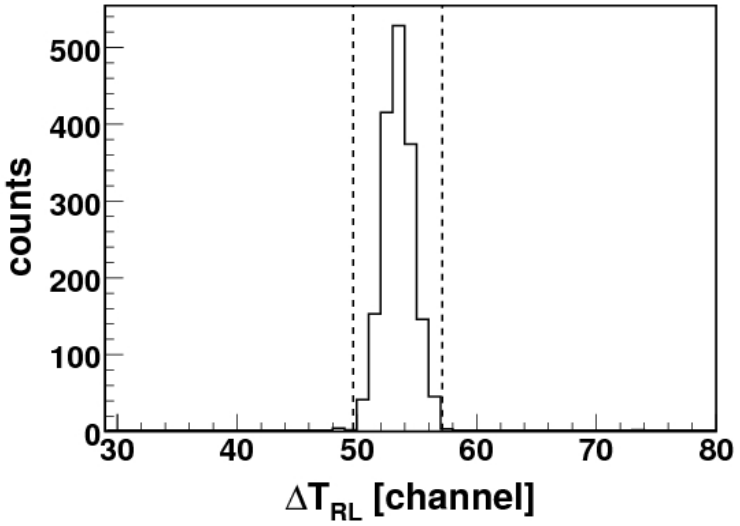
Correlations of the proton energies with the cut on missing mass (940MeV±10MeV) of deutron energy 500 MeV.

Measurement of the deuteron beam polarization at ITS using DSS detection system at 270 MeV

dp- elastic events selection

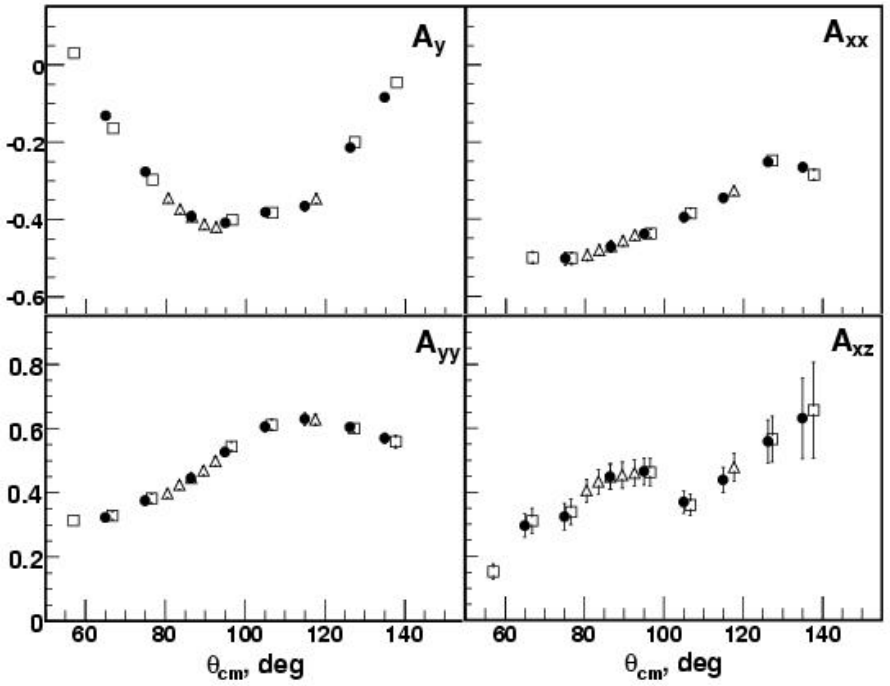


The correlation of the energy-loss signal for a pair of the deuteron and proton detector. The solid line is a graphical cut for the dp-elastic events selection.



The time difference between deuteron and proton detector for CH_2 target. The dotted line is a time gate for the dp-elastic events selection.

Measurement of the deuteron beam polarization at ITS using DSS detection system at 270 MeV



Vector Ay and tensor analyzing powers A_{yy}, A_{xx} and A_{xz} of dp- elastic scattering as a function of deuteron scattering angle in c.m.s. at deuteron beam energy of 270 MeV. □, Δ- the world data. Extrapolated values of the analyzing powers are marked by ●.

Cubic spline interpolation:

(x_i,y_i) на [A,B]

$f(x) = ax^3 + bx^2 + cx + d$

$f''(A) = f''(B) = 0$

K.Sekiguchi et al.,

Phys. Rev. C65 (2002) 034003

K.Sekiguchi et al.,

Phys. Rev.C70 (2004) 014001

K.Suda, et al.,

Nucl. Instr. Meth. in Phys. Res. A572 (2007) 745

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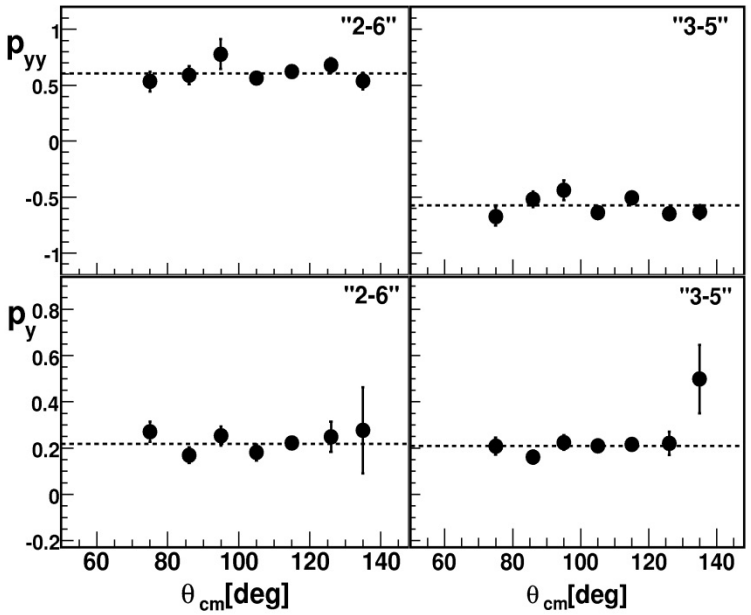
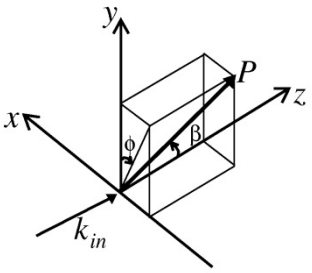


Tensor p_{yy} and vector p_y polarization of the beam for “2-6” and “3-5” spin modes of PIS POLARIS as a function of the deuteron scattering angle in the cms.

ß = -90.3º ± 1.2º

$$F^2 = \int \varepsilon A^2 d\Omega$$

Pzz=0.605 ± 0.025
Pz = 0.216 ± 0.015 “2-6”
Pzz=0.585±0.020
Pz = 0.208±0.012 “3-5”
Pzz=0.69±0.13 “LEP”

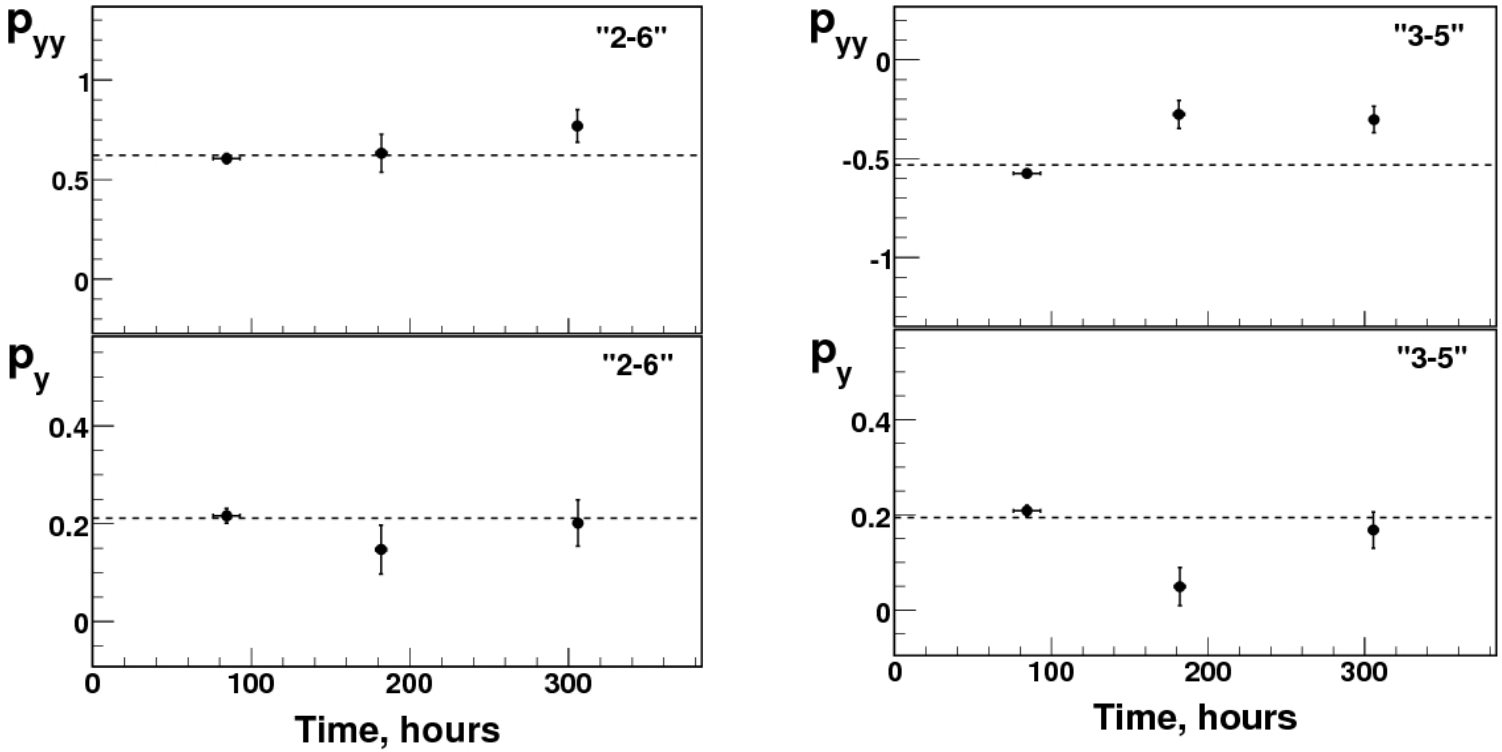


$F_{yy} \sim 1.8*10^{-4}$, $F_{xx} \sim 0.8*10^{-4}$

- **Reference deuteron beam polarimeter at Nuclotron.**

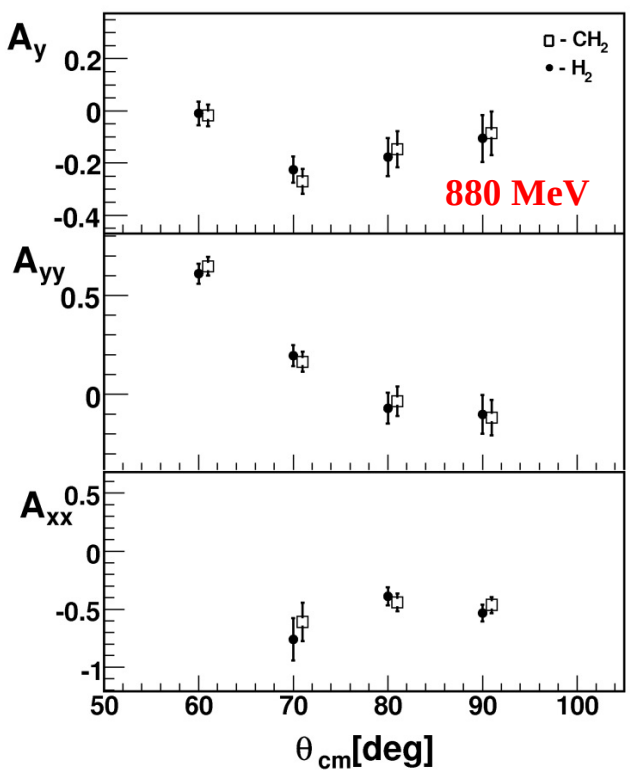
P.K.Kurilkin et al., Nucl. Instr. and Meth. A 642 (2011) 45

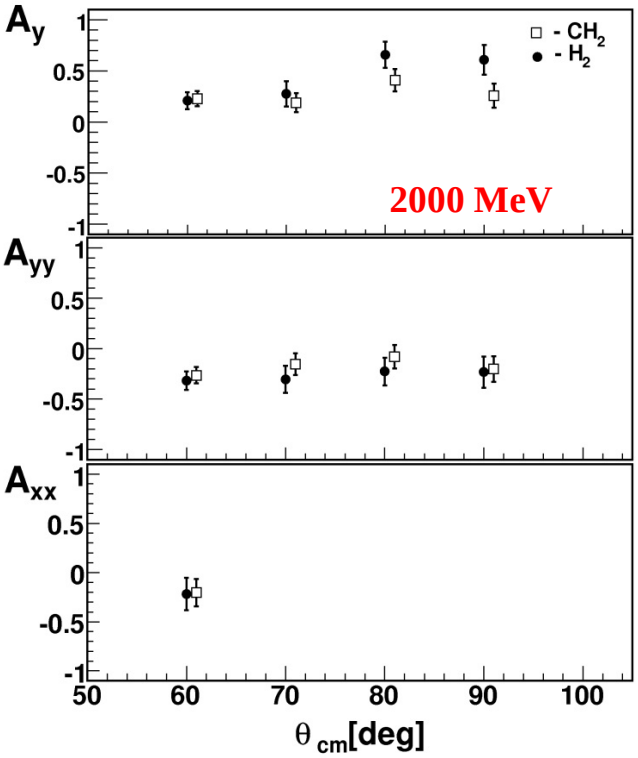
Long term stability of the beam polarization at 270 MeV



Tensor p_{yy} and vector p_y components of the deuteron beam polarization for "2-6" and "3-5" spin modes of PIS POLARIS as a function of the measuring time.

A_y, A_{yy} and A_{xx} in dp- elastic and quasielastic scattering at 880 and 2000 MeV





- **The analyzing powers in dp-elastic scattering are large enough to provide both the vector and tensor polarimetry at high energies.**
- **The analyzing powers values for elastic and quasielastic deuteron scattering are comparable. Therefore, polarimeter can used in the counting mode (without event-by-event analysis).**

Relativization schemes

For the case of the deuteron vertex the internal momentum **k**:

$$k = \sqrt{\frac{m_p^2 + \mathbf{k}_T^2}{4x(1-x)} - m_p^2},$$

$$x = \frac{E_p + p_{pl}}{E_d + p_d},$$

where $\mathbf{E_d}$ and $\mathbf{p_d}$ are the energy and momentum of the initial deuteron, respectively, $\mathbf{p_{pl}}$ is the longitudinal momentum of the proton, $\mathbf{m_p}$ and $\mathbf{E_p}$ are the mass and energy of the proton, respectively.

- Minimal relativization scheme (Dirac, Weinberg, Frankfurt& Strikman)
- Bete-Salpeter equation solving (Tjon&Keisler, Bondarenko et al.)
- Quasi-potential wave functions (Gross, Braun&Tokarev, Kaptari et al.)
- Covariant theory on the light cone (Karmanov et al.)

Deuteron wave function on the light cone

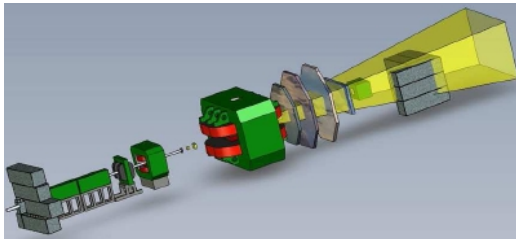
Relativistic deuteron wave function on light cone is defined by **6** invariant functions $\mathbf{f_1}, ..., \mathbf{f_6}$ (instead of **2** in the non-relativistic case), each of them depends on 2 scalar variables $\mathbf{k}$ and $z = cos(\widehat{\mathbf{kn}})$:

$$\psi(\mathbf{k},\,\mathbf{n}) = \frac{1}{\sqrt{2}}\sigma f_1 + \frac{1}{2}\left[\frac{3}{k^2}\mathbf{k}(\mathbf{k}\cdot\sigma) - \sigma\right] f_2 + \frac{1}{2}[3\mathbf{n}(\mathbf{n}\cdot\sigma) - \sigma]\, f_3 + \frac{1}{2k}[3\mathbf{k}(\mathbf{n}\cdot\sigma)$$
$$+\; 3\mathbf{n}(\mathbf{k}\cdot\sigma) - 2\sigma(\mathbf{k}\cdot\mathbf{n})]f_4 + \sqrt{\frac{3}{2}}\frac{i}{k}[\mathbf{k}\times\mathbf{n}]f_5 + \frac{\sqrt{3}}{2k}[[\mathbf{k}\times\mathbf{n}]\times\sigma]f_6,$$

$$(\mathbf{n}\cdot\mathbf{k}) = (\frac{1}{2} - \alpha)\cdot\sqrt{\frac{m_p^2 + \mathbf{p}_T^2}{\alpha(1-\alpha)}}.$$

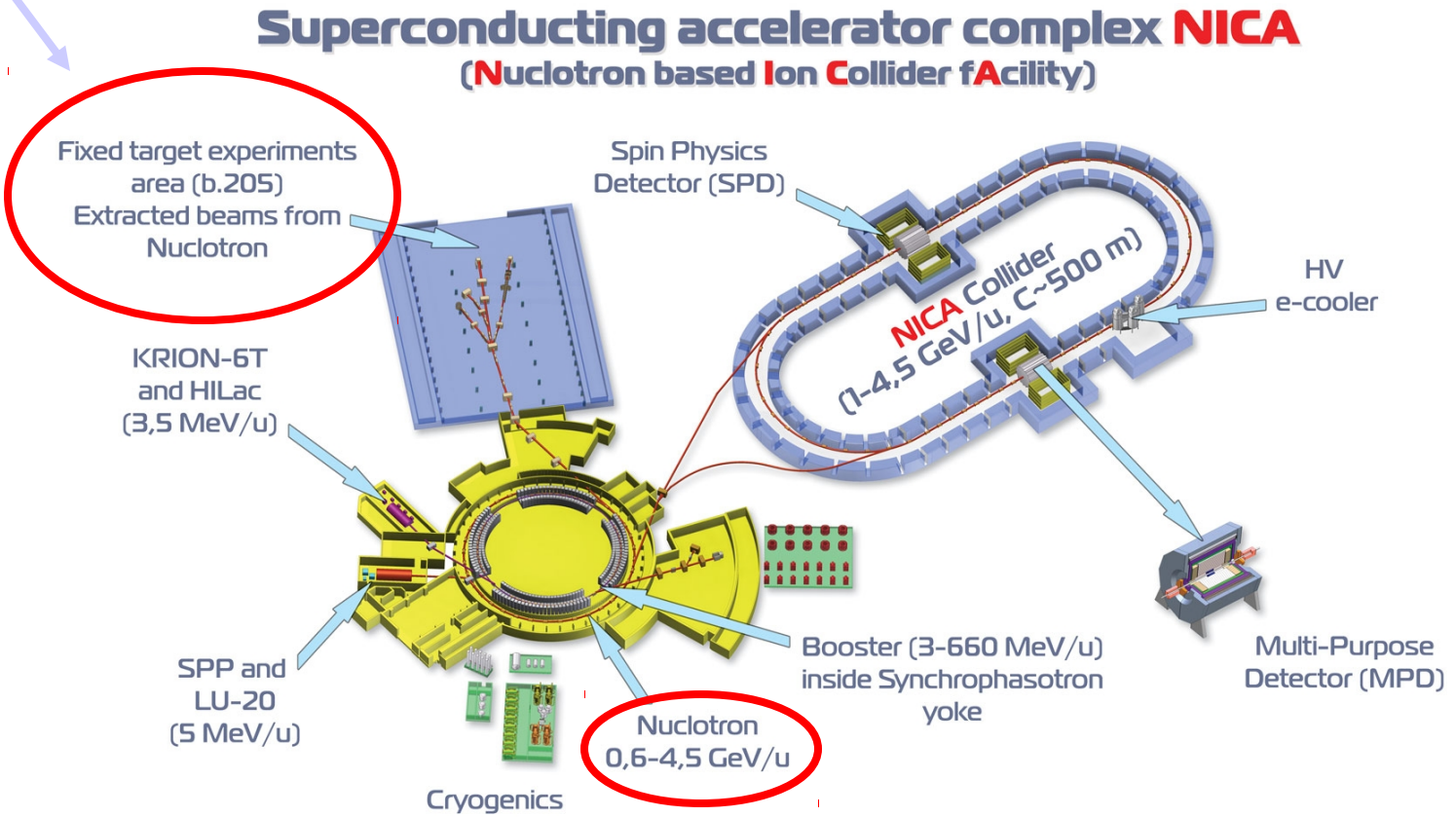
V.A.Karmanov, J.Carbonell et al.

The DSS and BM@N experiments



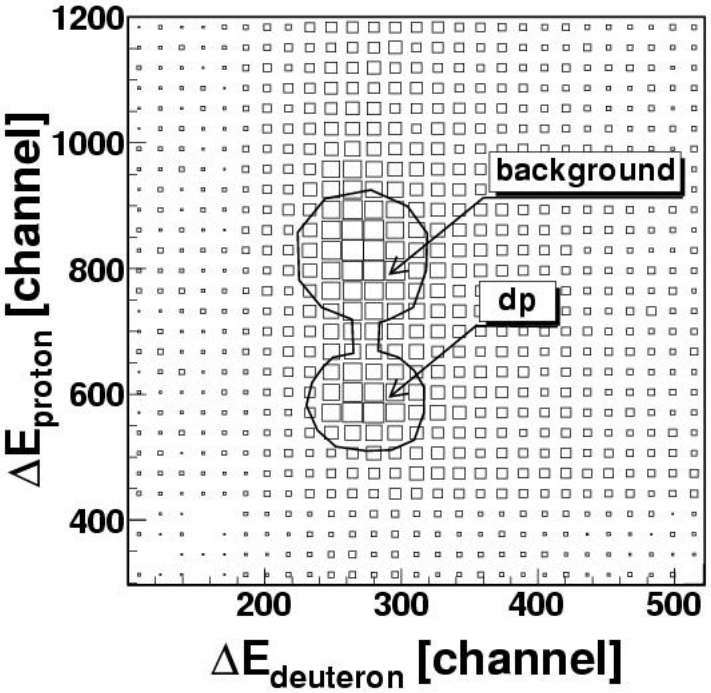
Nuclotron is a presently available facility which can accellerate *Au* up to 4.65 AGeV, *p* up to 12.6 GeV

DSS and BM@N are the fixed target experiments at the internal and extracted beams of Nuclotron, respectively.

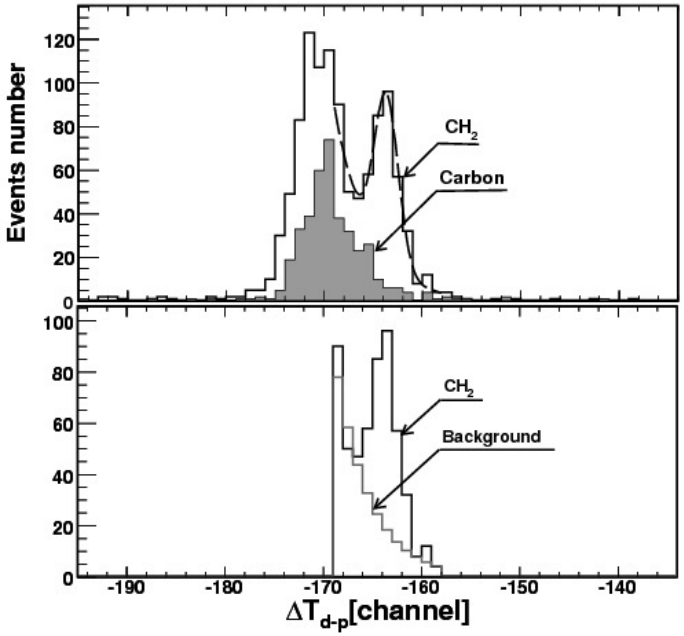


Analyzing powers measurement at 2000 MeV

The dp- elastic events selection

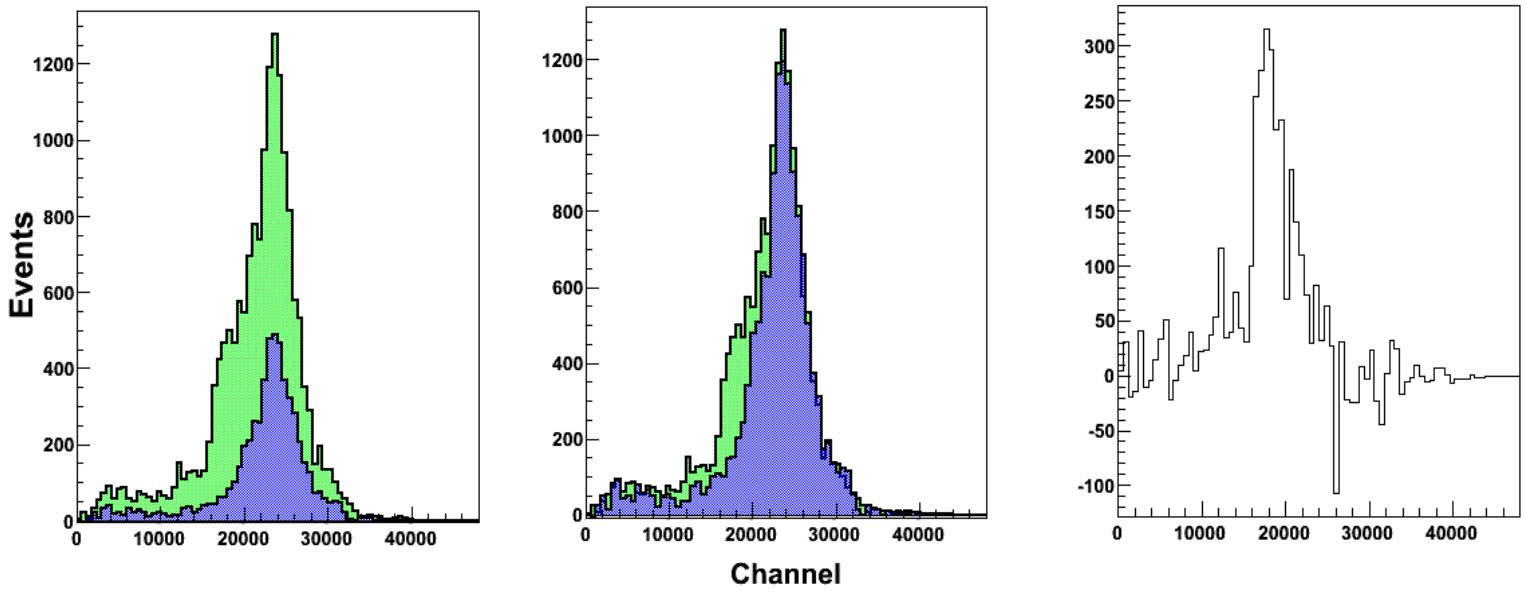


The correlation of the energy-loss signal for a pair of the deuteron and proton detector at 70° in c.m.s. The solid line is a graphical cut for the dp-elastic events candidate selection.



Selection of the dp elastic events by the time difference $\Delta T_{d\text{-}p}$ between the signal appearance from deuteron and proton detectors with the criteria on the amplitude signal correlation.

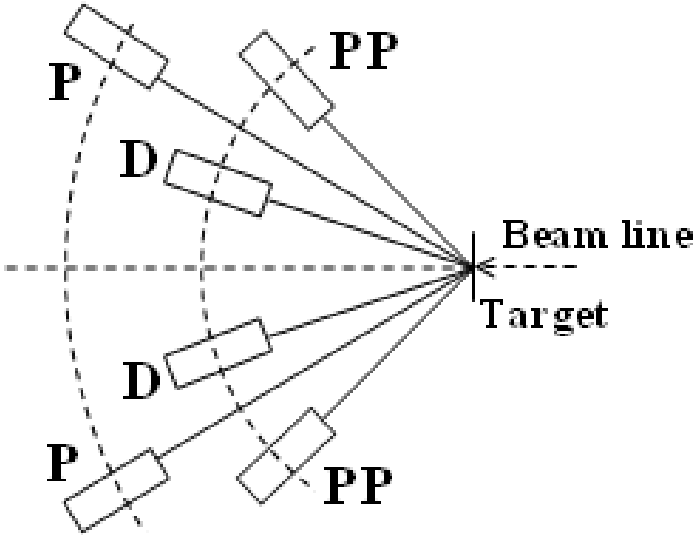
HE-dp- experiment data analysis

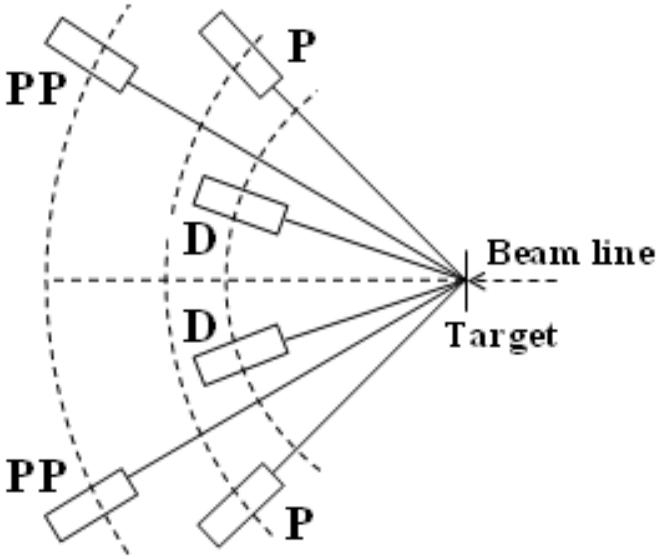


CH2-C subtraction for amplitude spectrum of P-counter.

The carbon backround arises with the deuteron energy significantly.

Scheme of the HE-dp- experiment

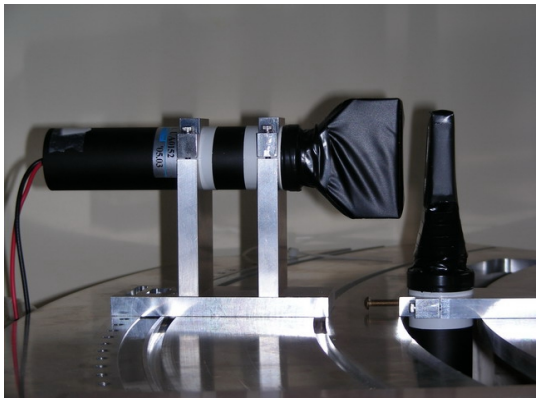




P = 20x60x20 mm^3

D = 10x40x24 mm^3

PP = 50x50x20 mm^3



P = 20x60x20 mm^3

D = 50x50x20 mm^3

PP = ϕ100x200 mm^3

March 2013-2015

December 2012

LE-dp- experiment has been performed with PMT-85 in 2011-2012