CNI polarimetry at the NICA accelerator collider complex

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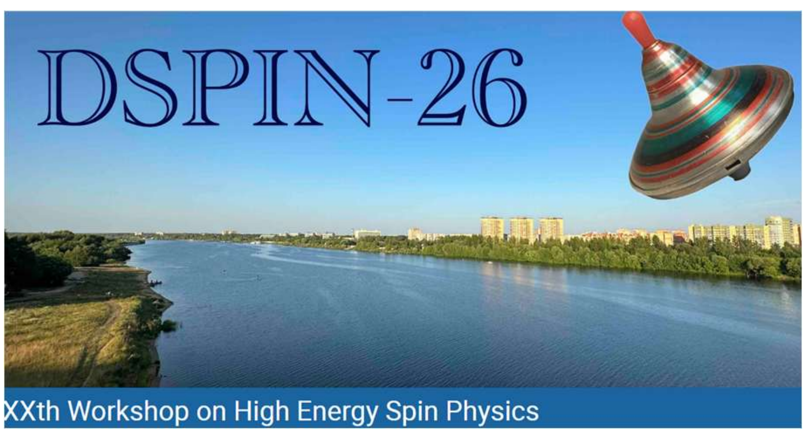
1. p-p, p-C, d-d, d-p, d-C elastic scattering in the CNI region.
2. Experimental data on p-Carbon CNI A_N in 2.3-24 GeV energy range.



The work was supported by a grant from the Russian Science Foundation:
No 25-72-30005, https://rscf.ru/project/25-72-30005/.

Concept for the polarimetry at Nuclotron-NICA

1. Efficient polarimeters at different key points of accelerator complex: LINAC, Nuclotron ring, booster, transportation lines, collider. Evaluation of the polarization standards for deuterons and protons.
2. Absolute calibration of the beam polarization for protons (and for deuterons-?).
3. The optimal usage of the same experimental equipment for the deuteron and proton polarimetry.
4. Permanent monitoring of the beam polarization by the basic polarimeters.
5. Local polarimetry at SPD, BM@N etc.

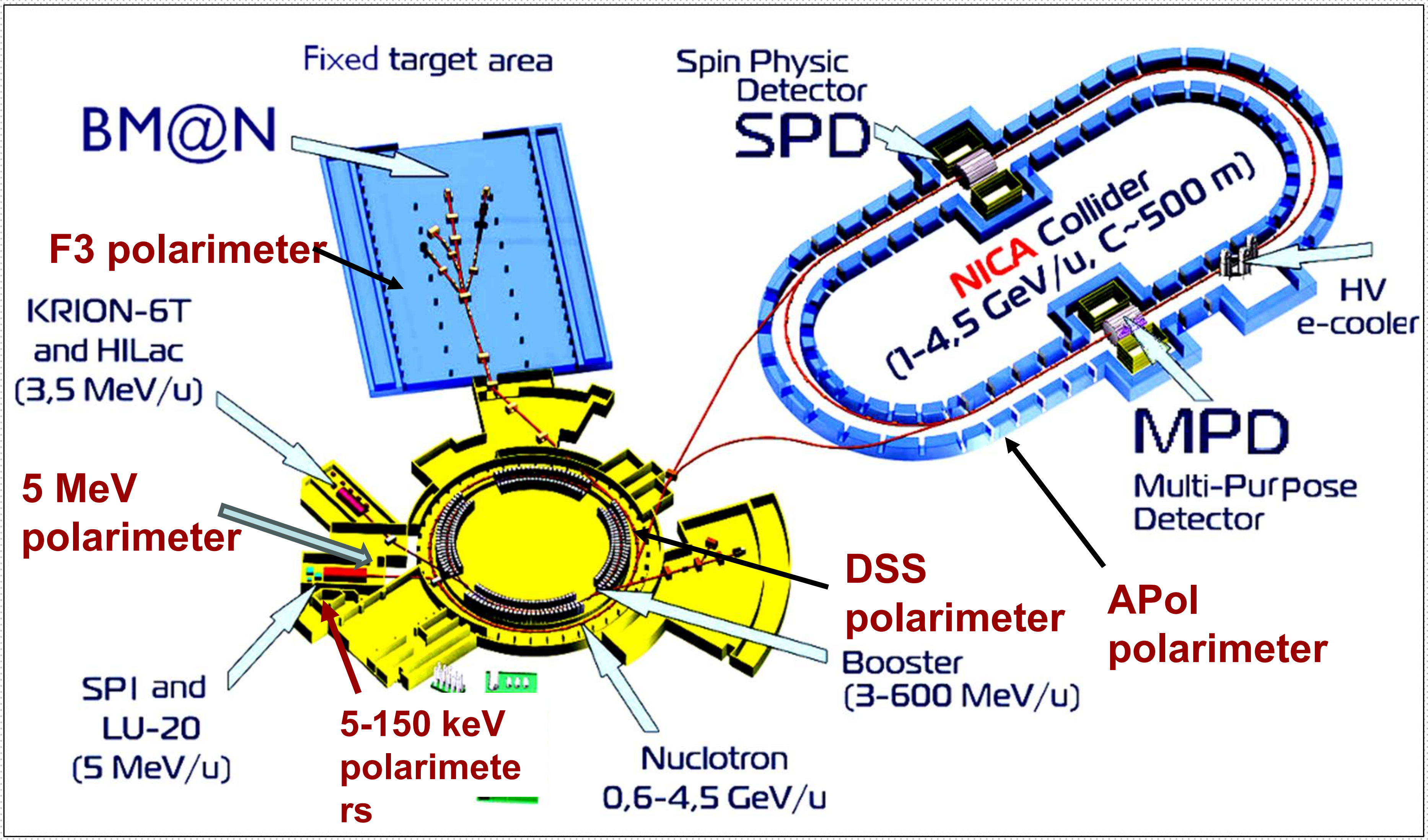
The goal is to have the systematic error due to beam polarization 5%

NICA distinctive features are polarized deuterons and
The Spin Transparency technique of the spin control.

V.P.Ladygin, JINR –SPRINT Collaboration

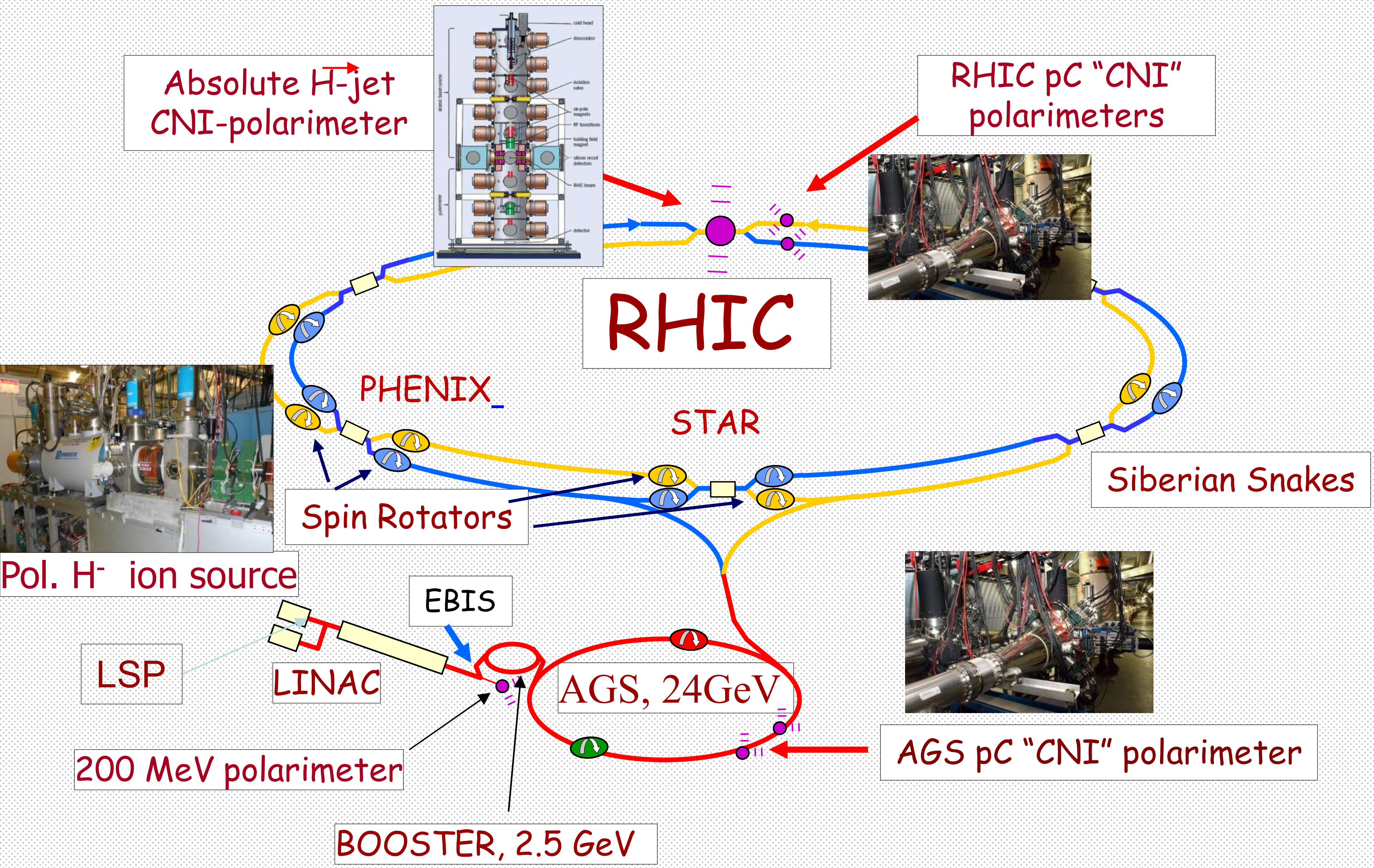
Поляриметры в ускорительно-накопительном комплексе NICA

$p\uparrow p\uparrow(p)$ at $\sqrt{s_{pp}}$ = **12 ÷ 27 GeV** (5 ÷ 12.6 GeV kinetic energy)
$d\uparrow d\uparrow(d)$ at $\sqrt{s_{NN}}$ = **4 ÷ 13 GeV** (2 ÷ 5.5 GeV/u kinetic energy)



Polarization facilities at RHIC

$L_{max} = 1.6 \times 10^{32}\ s^{-1} cm^{-2}$ $50 < \sqrt{s} < 510$ GeV



Proton-carbon CNI polarimeters in the Nuclotron and NICA collider

- The need for high efficiency polarmeters.
- For this purpose, in addition to the existing polarimeter with an internal target in the Nuclotron, polarimeters based on elastic proton-proton or proton-carbon scattering with a small momentum transfer in the CNI region can be used. The analyzing power of this polarimeters is about 4% for the scattering of protons on carbon.
- For deuterons analyzing power is expected to be smaller, but still usable for relative measurements and spin direction alignment.

A_N: from where does it come?

$$\sigma = |A_{hadronic} + A_{Coulomb}|^2 \qquad (|\mathbb{P}+\gamma|^2)$$

around $t \sim -10^{-3}\,(\text{GeV}/c)^2$ $A_{hadronic} \approx A_{Coulomb} \Rightarrow$ INTERFERENCE

CNI = Coulomb – Nuclear Interference

unpolarized $\Rightarrow$ clearly visible in the cross section $d\sigma/dt$ (charge)

polarized $\Rightarrow$ left – right asymmetry A_N (magnetic moment)

$$A_N = C_1 \Phi_{em}^{flip} \Phi_{had}^{non-flip} + C_2 \Phi_{had}^{non-flip} \Phi_{had}^{flip}$$

$\propto(\mu-1)_p$ $\qquad \propto\sqrt{\sigma^{pp}}_{had}$

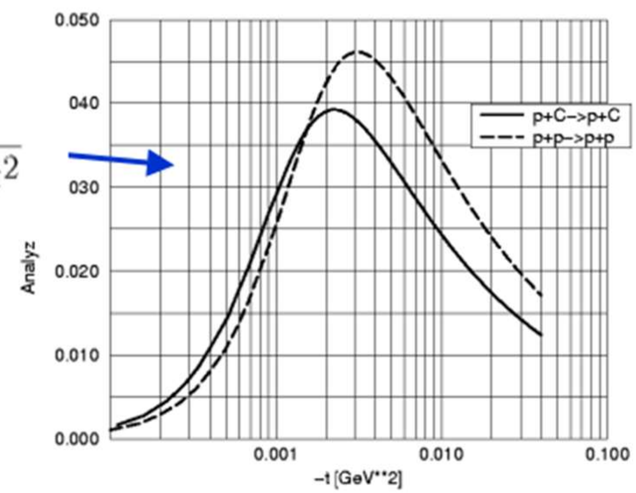
QED $\Rightarrow$ "calculable", expect $A_N \neq 0$ up to 4 – 5%

$$A_N^{int} = \sigma_{tot} \times \frac{\alpha}{m_p\sqrt{-t}} \frac{\mu_p - 1}{2} \frac{1}{\sigma_{tot}^2/16\pi + 4\pi\alpha^2/t^2}$$

hadronic non-flip $\qquad$ EM spin flip

QCD $\Rightarrow$ "unpredictable", need direct measurement

$$\frac{\mu_p - 1}{2} \to \frac{\mu_p - 1}{2} - I_5 + \frac{\mu_p - 1}{2} I_2$$

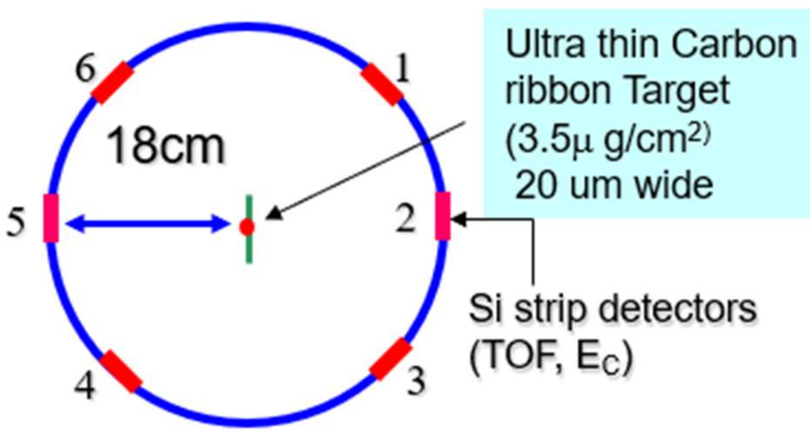


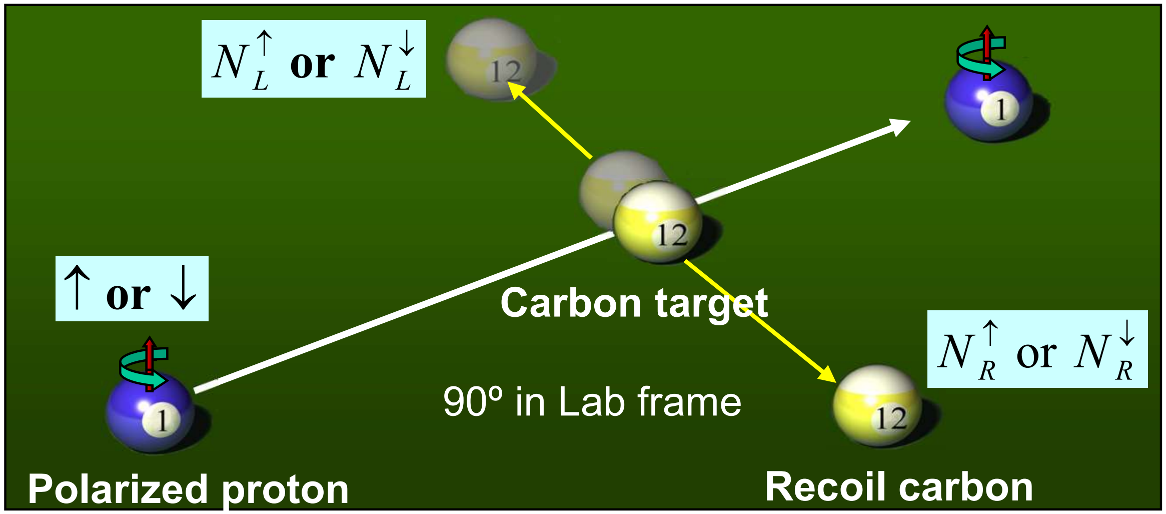
B.Z. Kopeliovich and L.I. Lapidus, Yad. Fiz. 19 (1974) 218 [Sov. J. Nucl. Phys. 19 (1974) 114

CNI polarimetry

- The large cross-sections of elastic scattering at small ~ |t| ~0.002–0.01 (GeV/c)2 makes it possible to obtain a high counting rate, when using a very thin (~10 atomic layers of 5 μg/cm2, 25-50 nm thick and with a width of ~ 10-100 μm) carbon film targets.
- These targets applications makes *it possible to use the multiple passage of the beam through the target,* which increases the efficiency of the polarimeter.
- Polarimeters with such targets have been developed and used at BNL in the energy range of 2.3-24 GeV in AGS (Alternating Gradient Synchrotron) and up to 255 GeV in the RHIC [17].
- Such targets are made by sputtering (through a mask) carbon vapors evaporated by an electron beam on a glass substrate.

proton-Carbon CNI Polarimetry at AGS and RHIC.



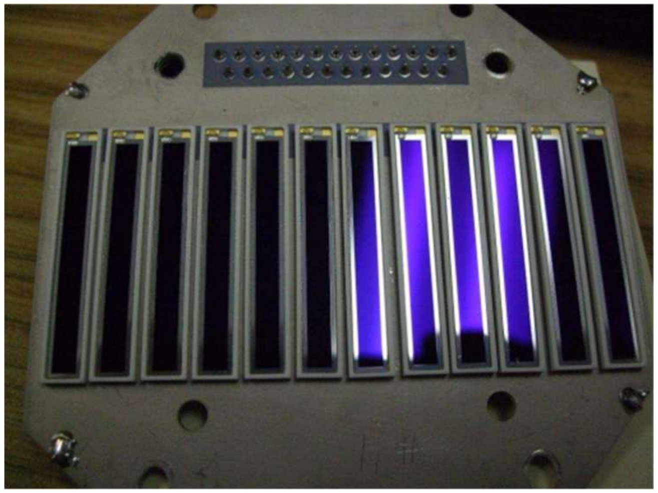


Very thin target.
Non-destructive !!!

$$t = (p_{out} - p_{in})^2 \approx -2M_C T_{kin} < 0$$
$$0.005 < |t| < 0.05\ (GeV/c)^2$$

RHIC detectors

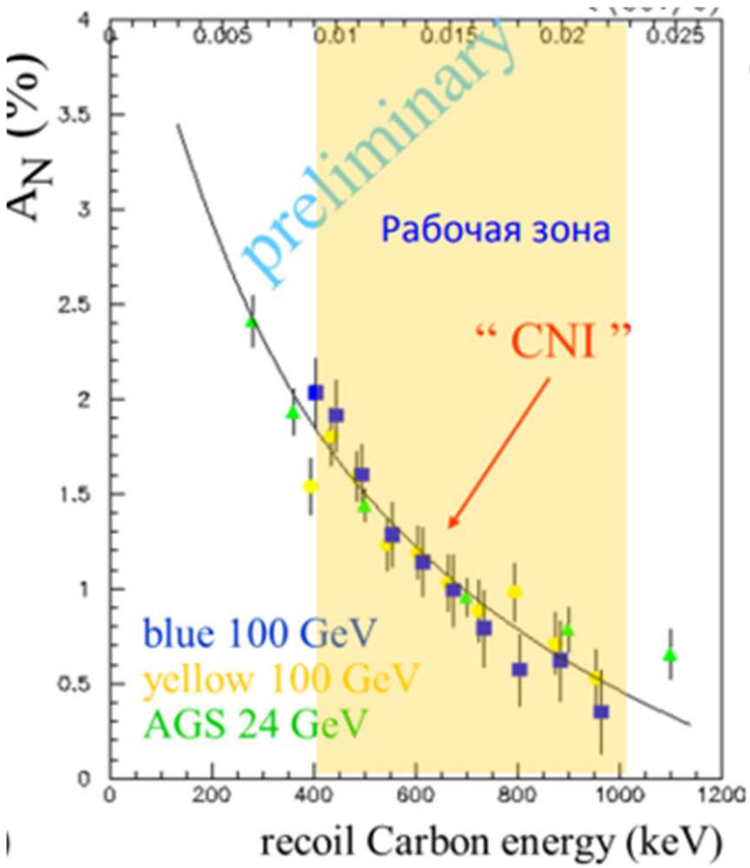
AGS detectors

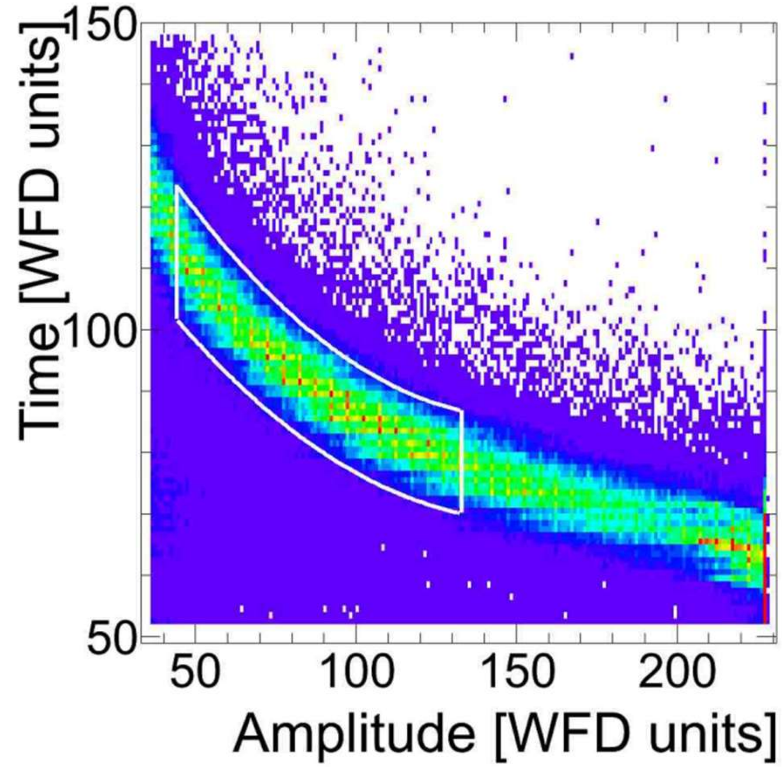


Windowless silicon detectors are specialized semiconductor sensors that lack a traditional protective physical window over the active sensor area to eliminate signal attenuation, and low-penetration particles. Small "dead" layer.

CNI polarimeter targets

- Polarimeters with such targets have been developed and used at BNL in the energy range of 2.3-24 GeV in AGS (Alternating Gradient Synchrotron) and up to 255 GeV in the RHIC [17].
- Such targets are made by sputtering (through a mask) carbon vapors evaporated by an electron beam on a glass substrate.
- Energy of registered carbon recoil nuclei is low 400-900 keV , so the use of thin targets is also necessary to reduce absorption in the target.





Elastic event signature

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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

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Carbon micro-ribbon and strip polarimeter targets for the AGS and RHIC☆

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Available online 5 March 2008

Very thin target.
Non-destructive !!!

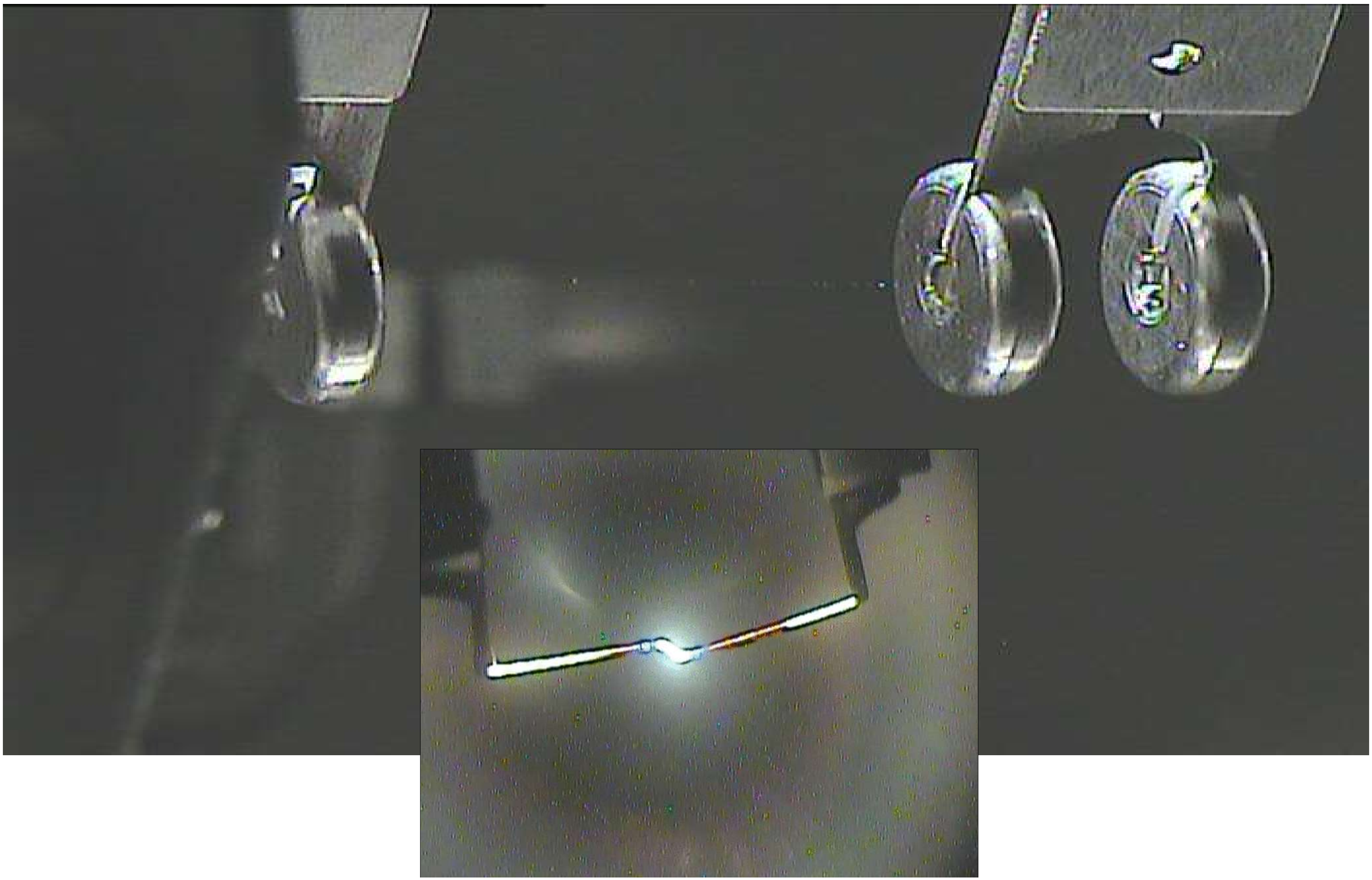
Abstract

Current techniques used to produce carbon micro-ribbon targets 5 μm wide × 3.7–4.5 μg/cm^2 × 25-mm long will be described. Developmental emphasis was to provide nearly identical micro-ribbons with the minimum number of atoms per unit of length, and to position them within ±0.5 mm of the desired location on C-shaped frames.

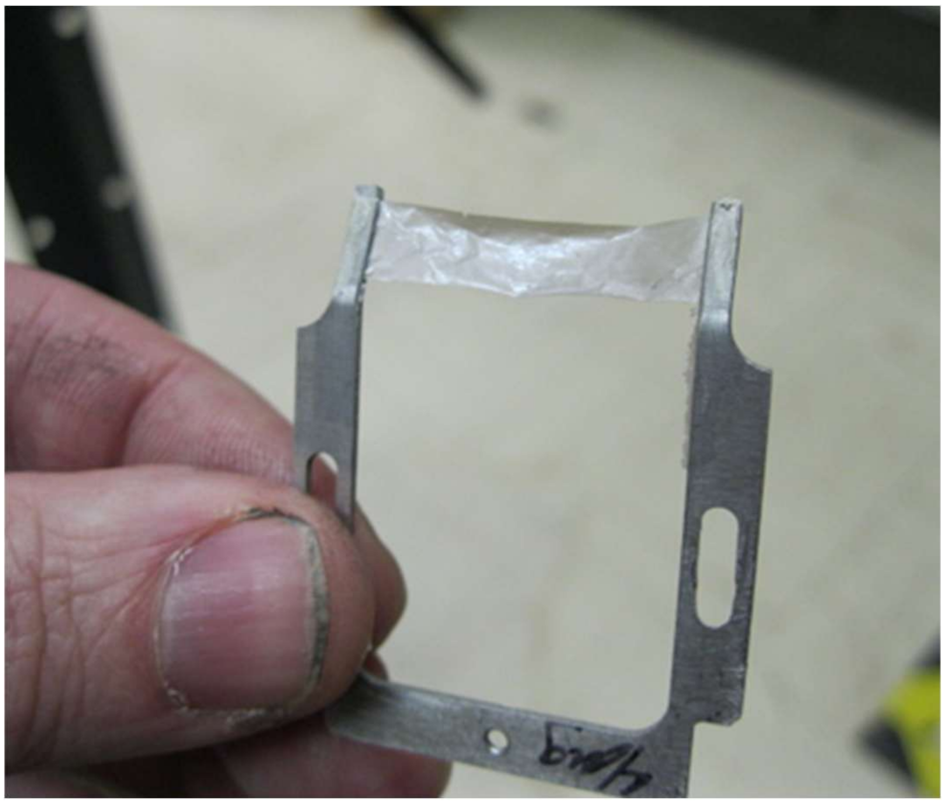
The foil strip targets to be described were 200–600 μm wide × 3.7–4.5 μg/cm^2 × 51 mm long. These were produced from 25-mm-wide carbon film deposits that were scribed using a jig prior to dissolving the betaine/sucrose release agent under ethanol.

Both types of targets required methods and devices that differed significantly from those reported previously for substrate texturing, masking, vacuum deposition, releasing from the substrate, and mounting. Sets of 12–24 of the targets have been made for the 2006 run period at BNL.

Very thin Carbon strip target-20um x 25 nm
L=25 mm-RHIC

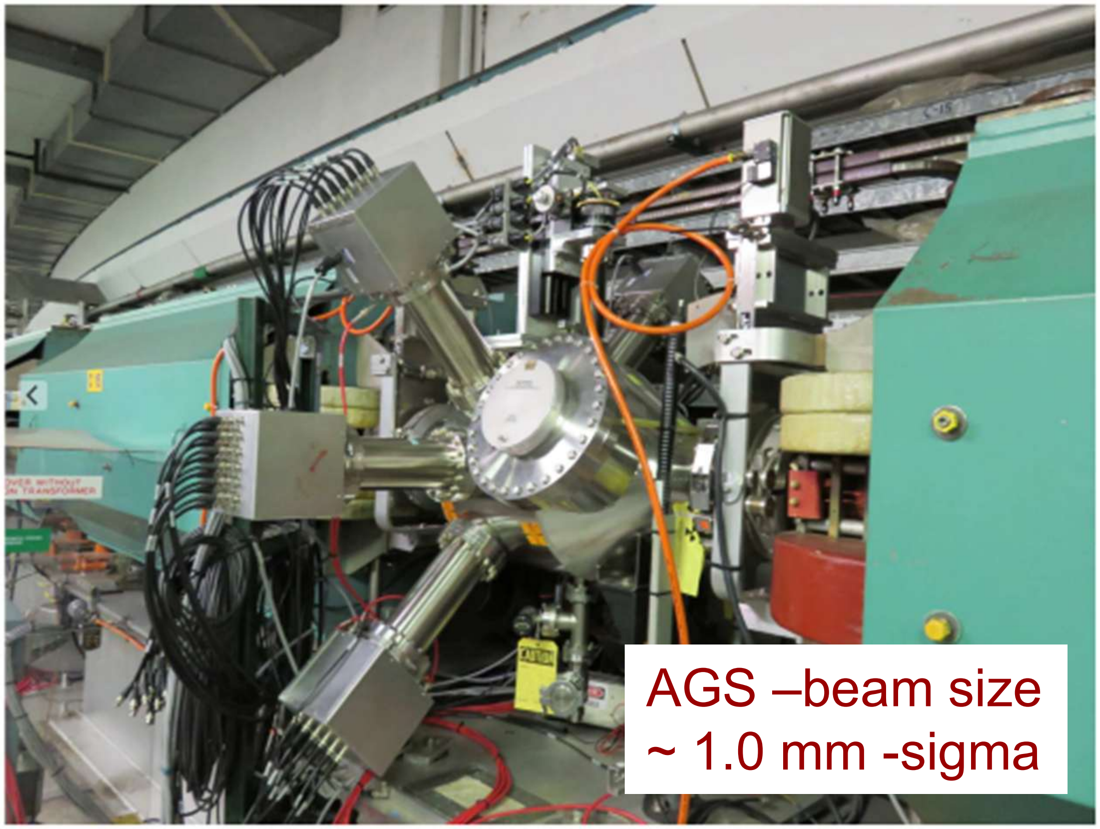


Wide target produced by laser ablation technique ~3 times stronger

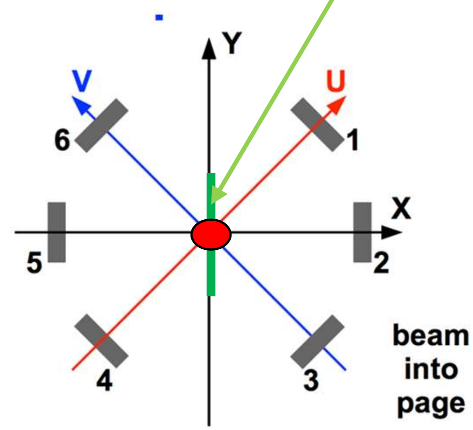


~ 25-30 nm thickness,
~ 4 micro-gram/ cm2

AGS –p-Carbon CNI polarimeter



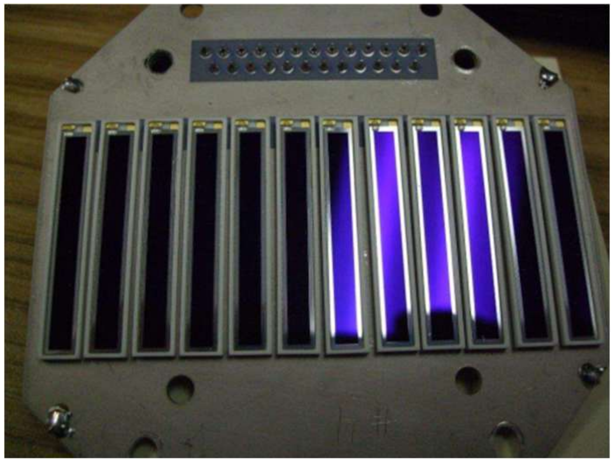
Carbon ribbon Target, 50 -150 um wide
3.5 μg/cm^2 ~ 1.8*10^17 atoms/cm2

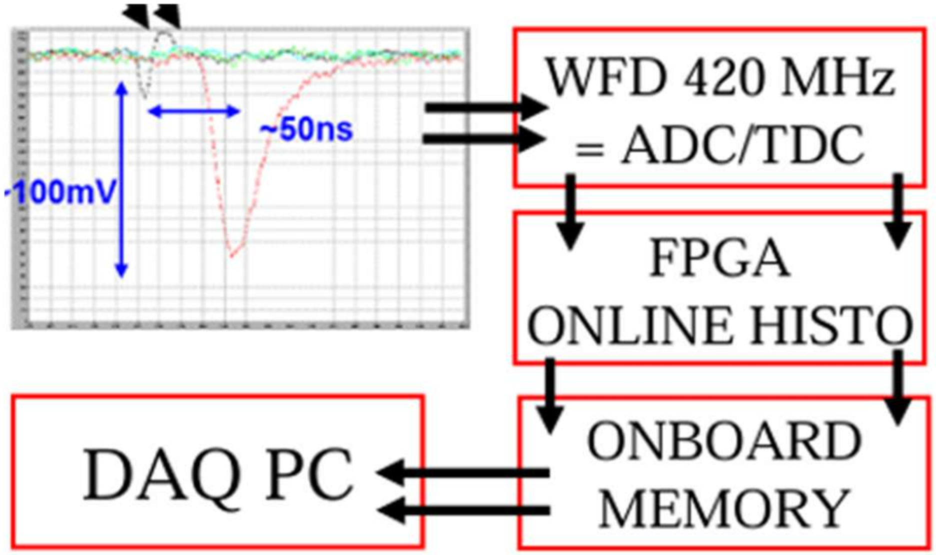


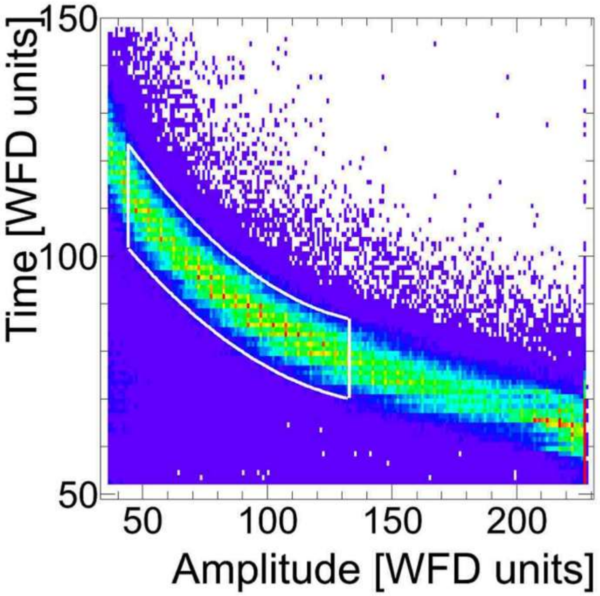
There are three pairs of detectors. The pairs at ±45◦ measure both horizontal and vertical polarization components. The pair at 90◦ measures vertical component only.

A typical measurement (40M events) takes ~ 40 spills x 3.5 s ~3 min. and provides the statistical accuracy of the measured polarization of about P ~ 2%.
Bunch intensity – 2-3 *10^11 protons/bunch. One bunch in the ring (810 meters long.) ~2.6 us bunch spacing.
~ 2*10^5 – target crossings in 600 ms ramp time

- Multi-strip silicon detectors are used as detectors of carbon recoil nuclei. Carbon recoil nuclei are identified by the time-of-flight and energy (as measured by a WFD-wave-form digitizer).



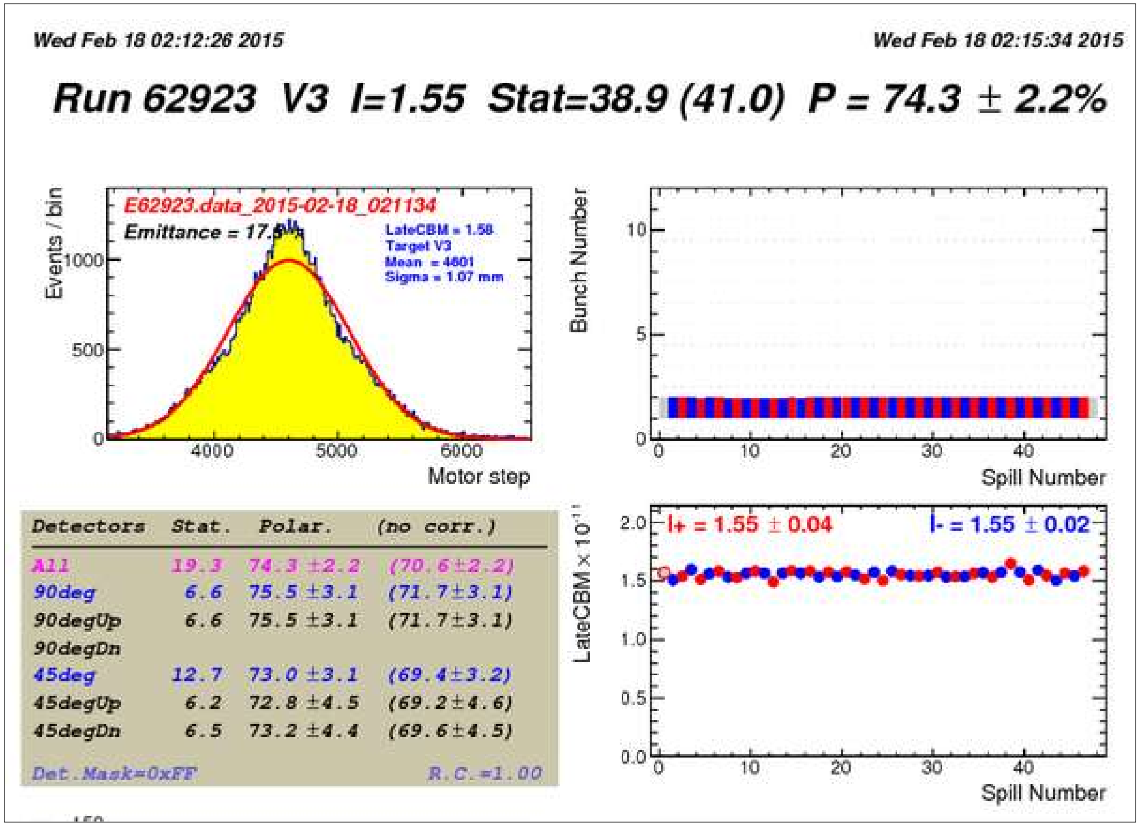


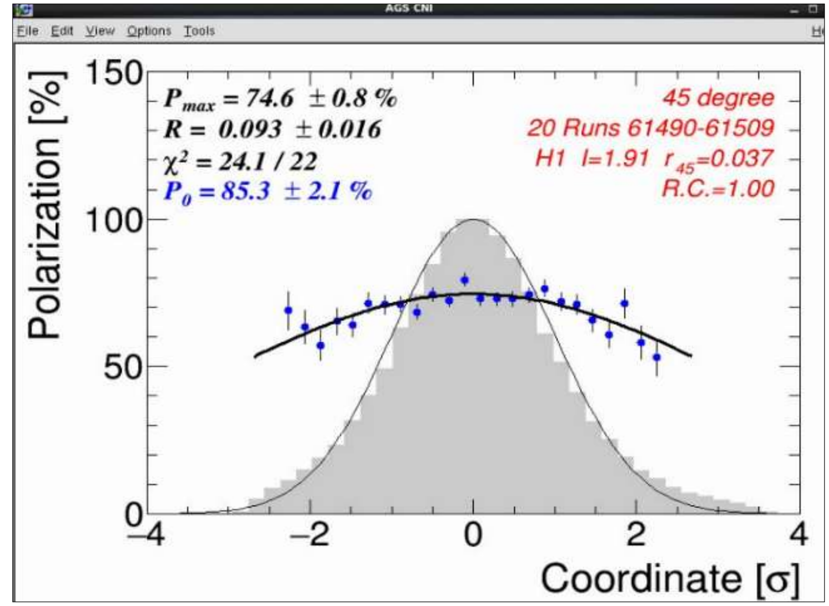


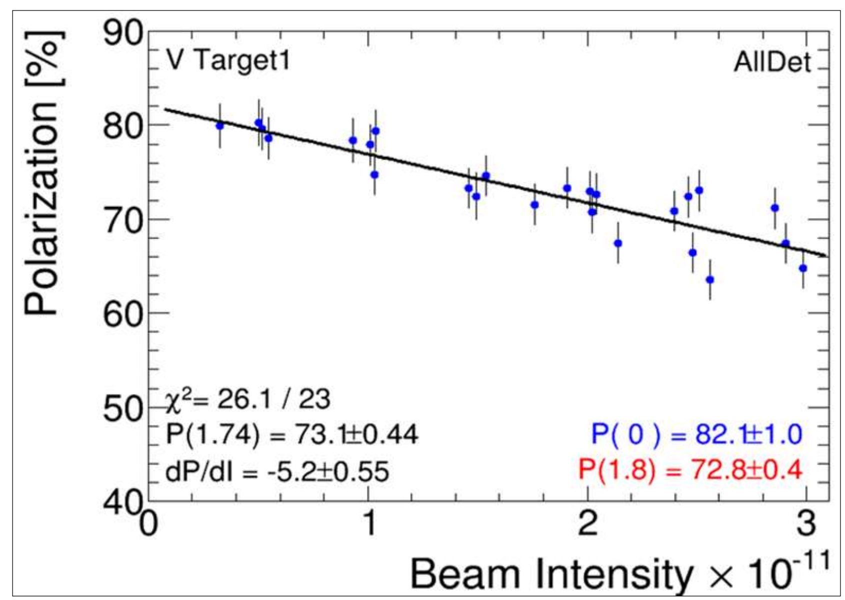
Windowless silicon detectors are specialized semiconductor sensors that lack a traditional protective physical window over the active sensor area to eliminate signal attenuation, and low-penetration particles. Small "dead" layer.

Elastic event signature

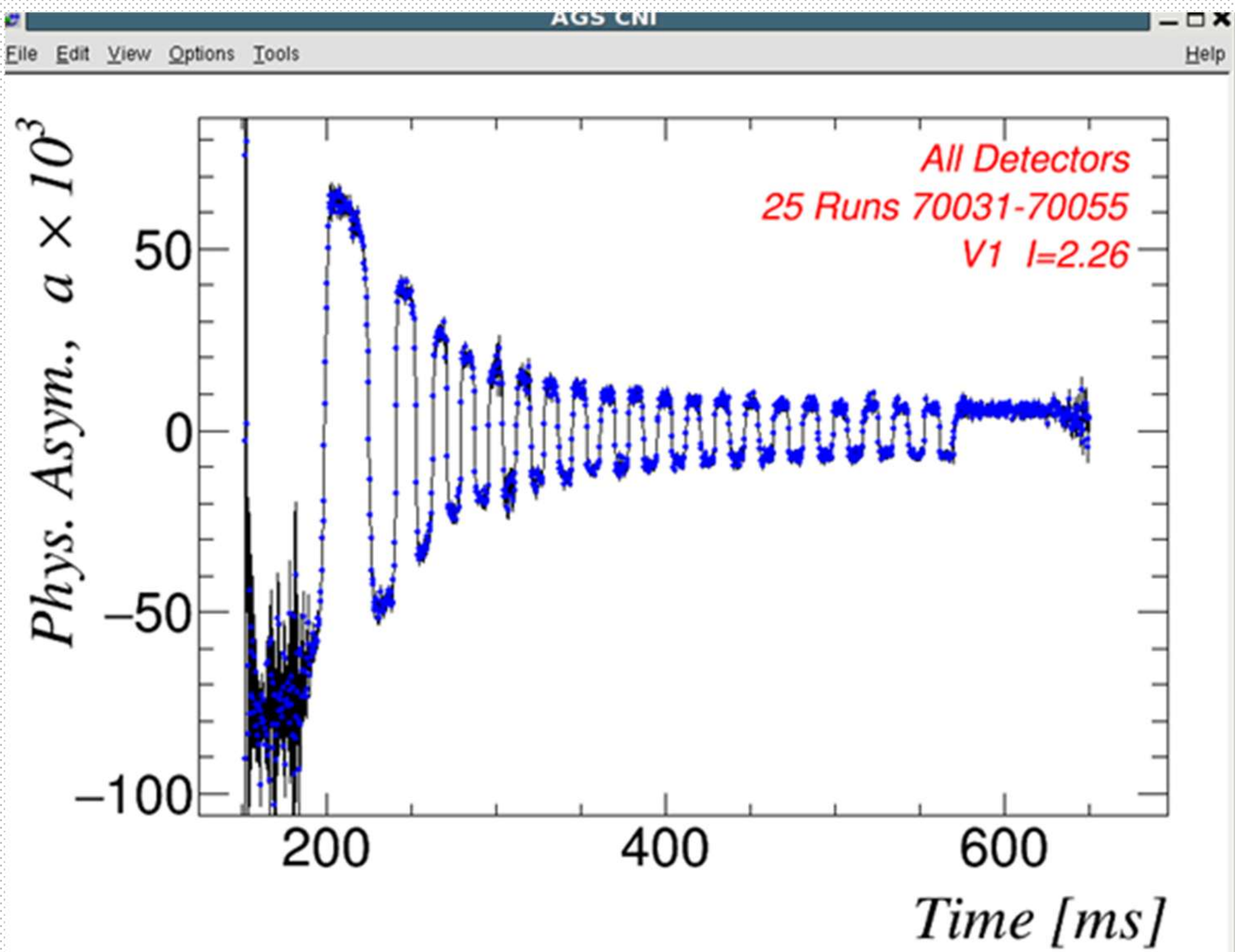
Polarization in AGS, 23 GeV





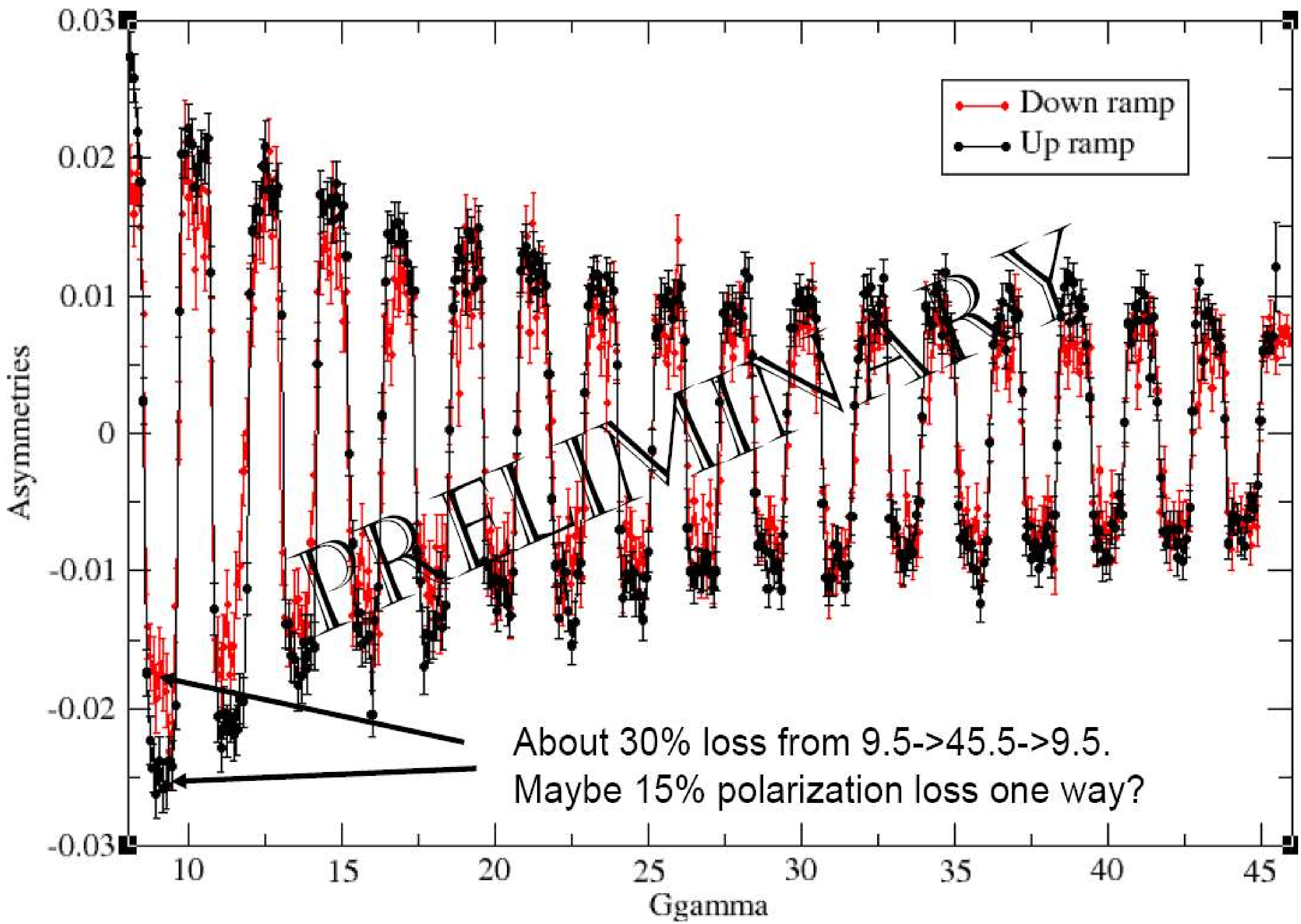


The asymmetry measured on the AGS ramp as function real time. The spin flips at every integer of Gγ are due to the presence of two partial Siberian snakes.

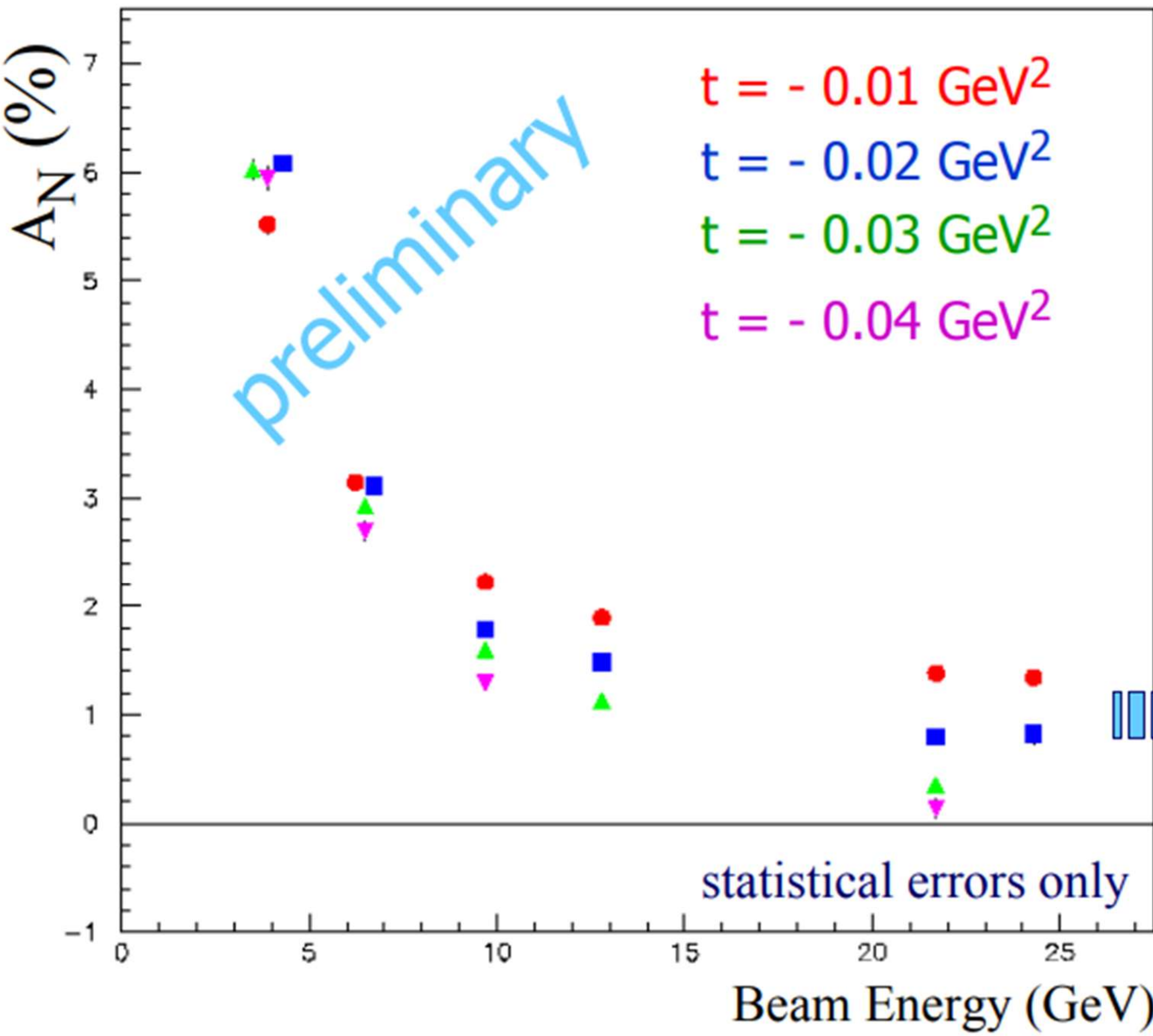


2.3 to 23.4 GeV energy ramp.
Polarization losses -80 to 70 %

Polarization measurements on the energy ramp in AGS.



A_N $p^{\uparrow}C \rightarrow pC$: Energy Dependence



only statistical errors are shown
systematic errors as for previous slide

Asymptotic regime

E ?

No energy dependence

CNI polarimetry

- With a typical intensity of polarized protons in a bunch ~ 2.5·10^11 (protons/bunches) and a measurement time of ~ 1000 ms, the number of events recorded in all parallel detectors is 1 million/AGS acceleration cycle.
- To measure with 2% statistical accuracy, 40 million events has to be collected, which required ~ 40 AGS cycles of the accelerator in 4 seconds each, i.e. approximately 160 seconds.
- Such a polarimeter with a thin carbon target can also be used to measure polarization, as well as polarization profiles at the Nuclotron and the NICA collider.
- *Since the carbon nuclei in the CNI polarimeter are detected at angles close to 90 degrees, the polarimeter can be very compact, which simplifies installation in the collider rings.*
- The use of a measurement system of 6 detectors allows also to measure the direction of polarization.
- It is also possible to combine the CNI polarimeter and the detection of scattered protons (deuterons) in one device (in one vacuum chamber and one target station), with larger momentum transfers and optimization of the measurement configuration for different energies and beam intensities, as well as deuterons polarization measurements.

Polarization facilities at RHIC

$L_{max} = 1.6 \times 10^{32}\ s^{-1}cm^{-2}$ $50 < \sqrt{s} < 510$ GeV

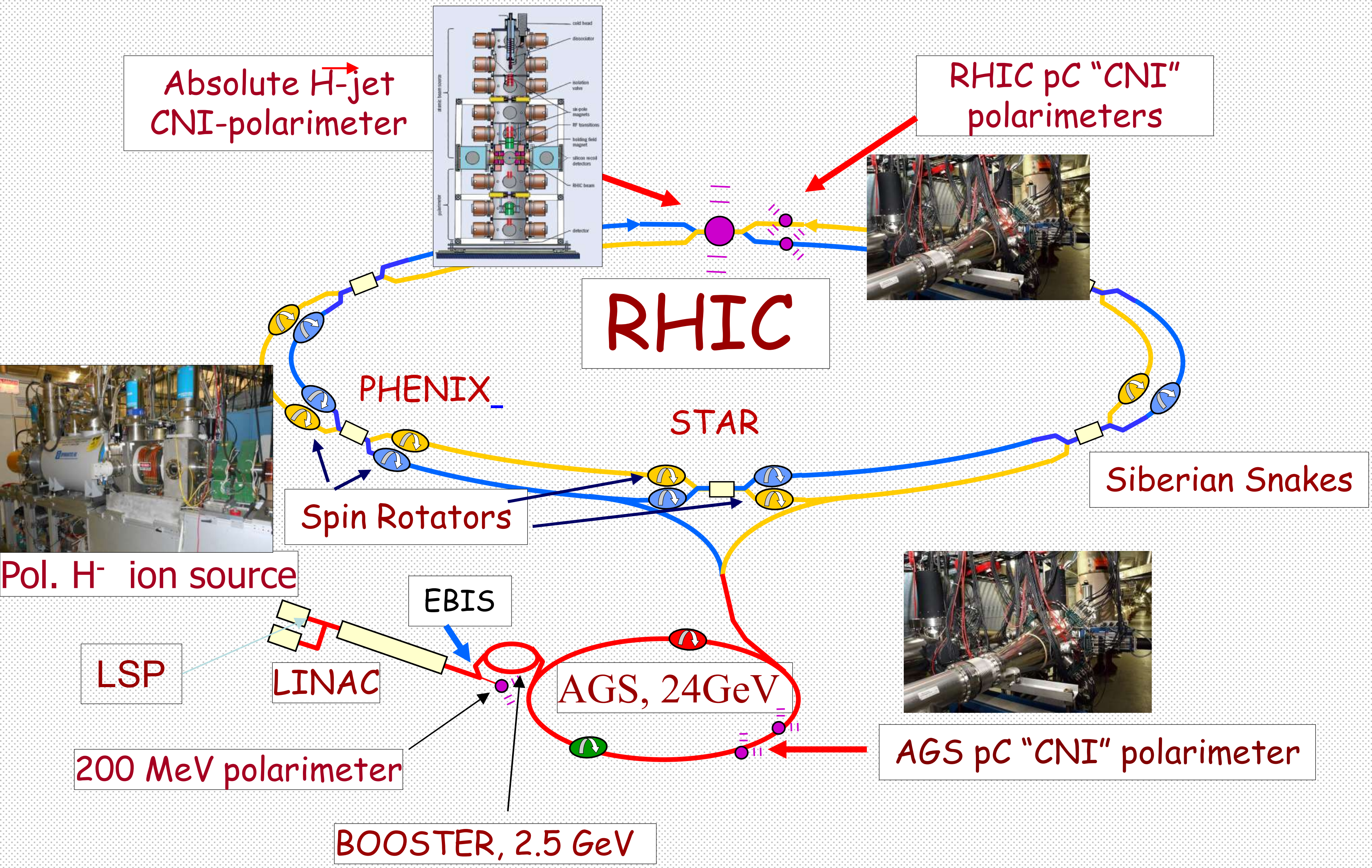
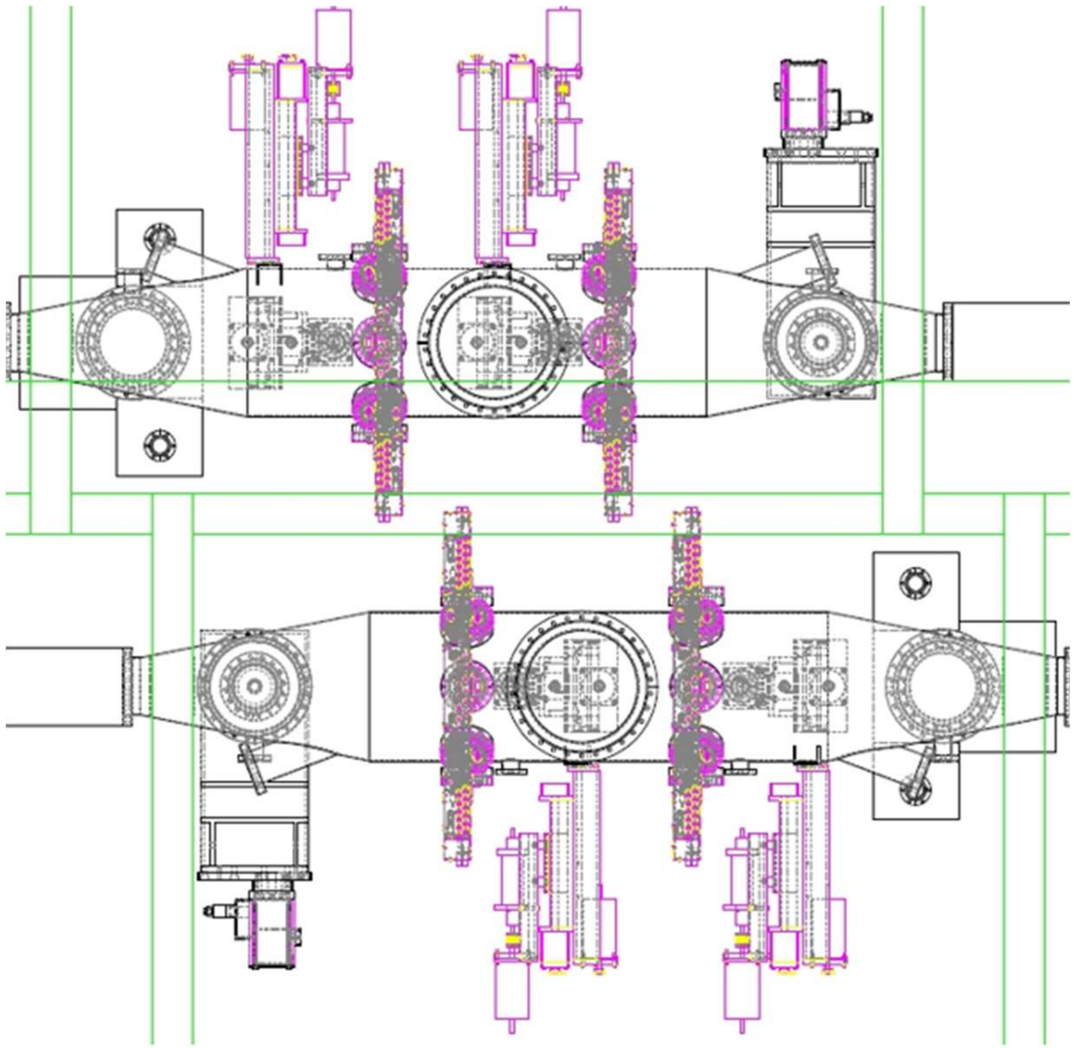
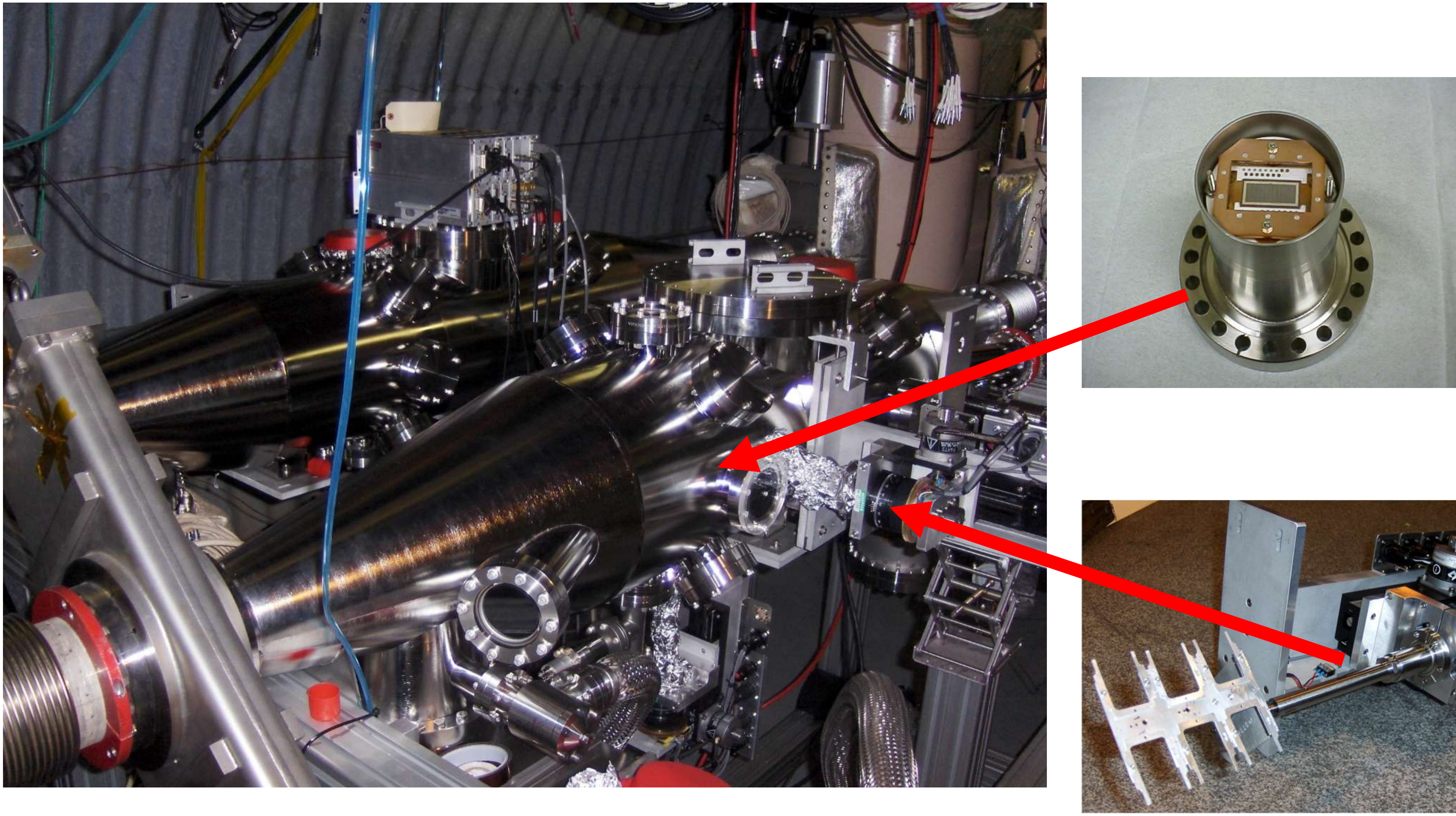


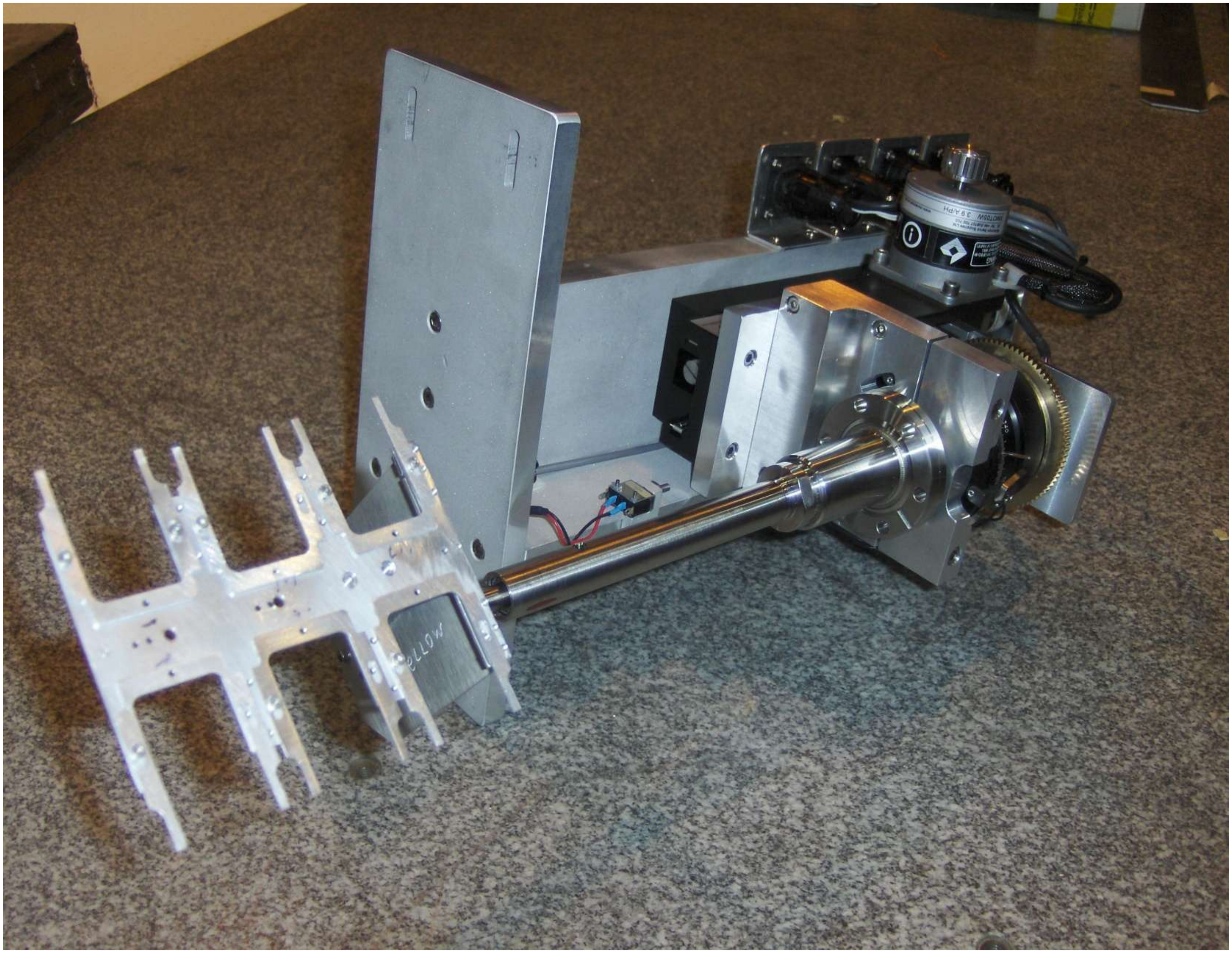
Схема вакуумной системы, мишенных узлов и детекторов поляриметров RHIC.

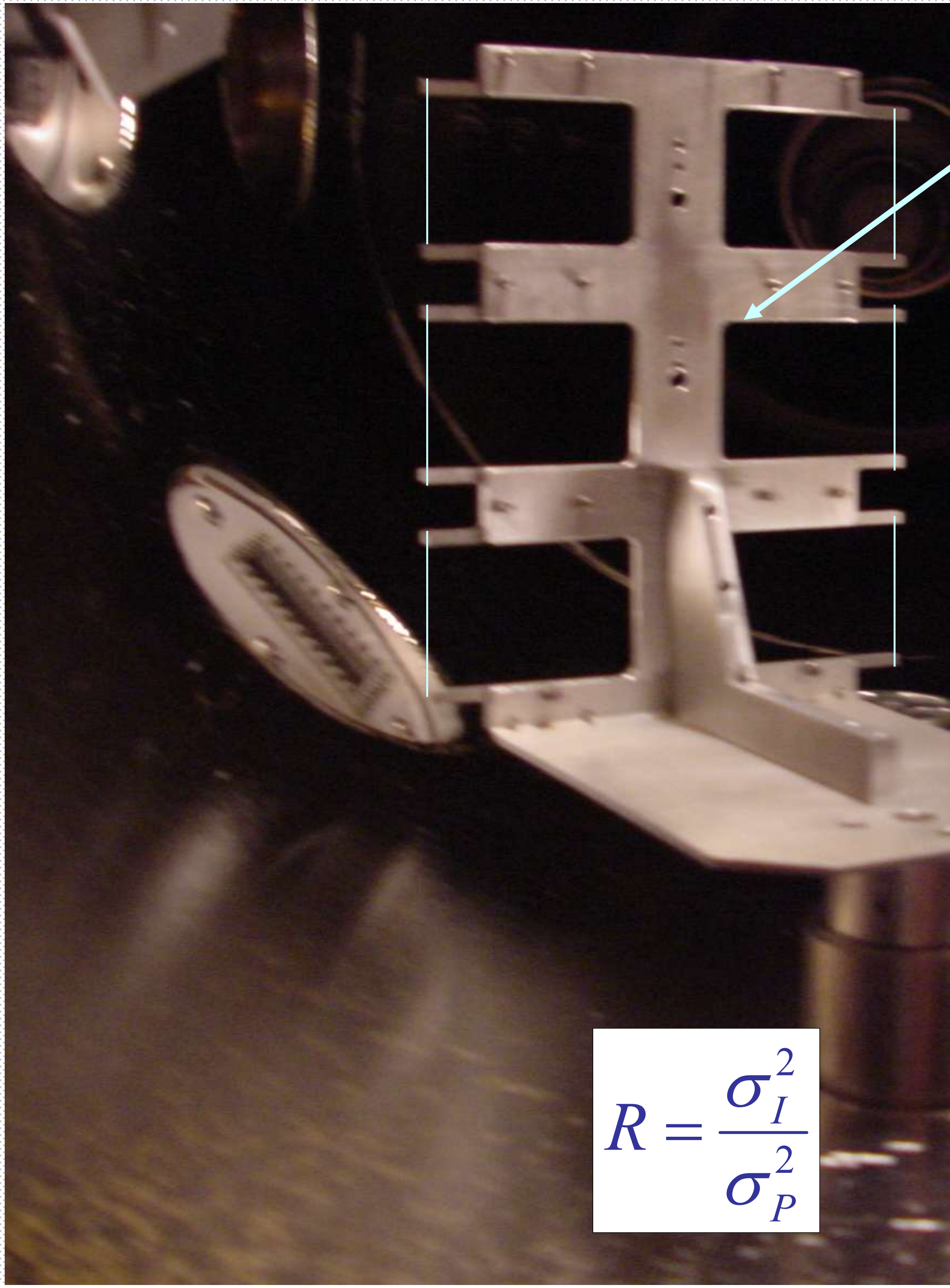


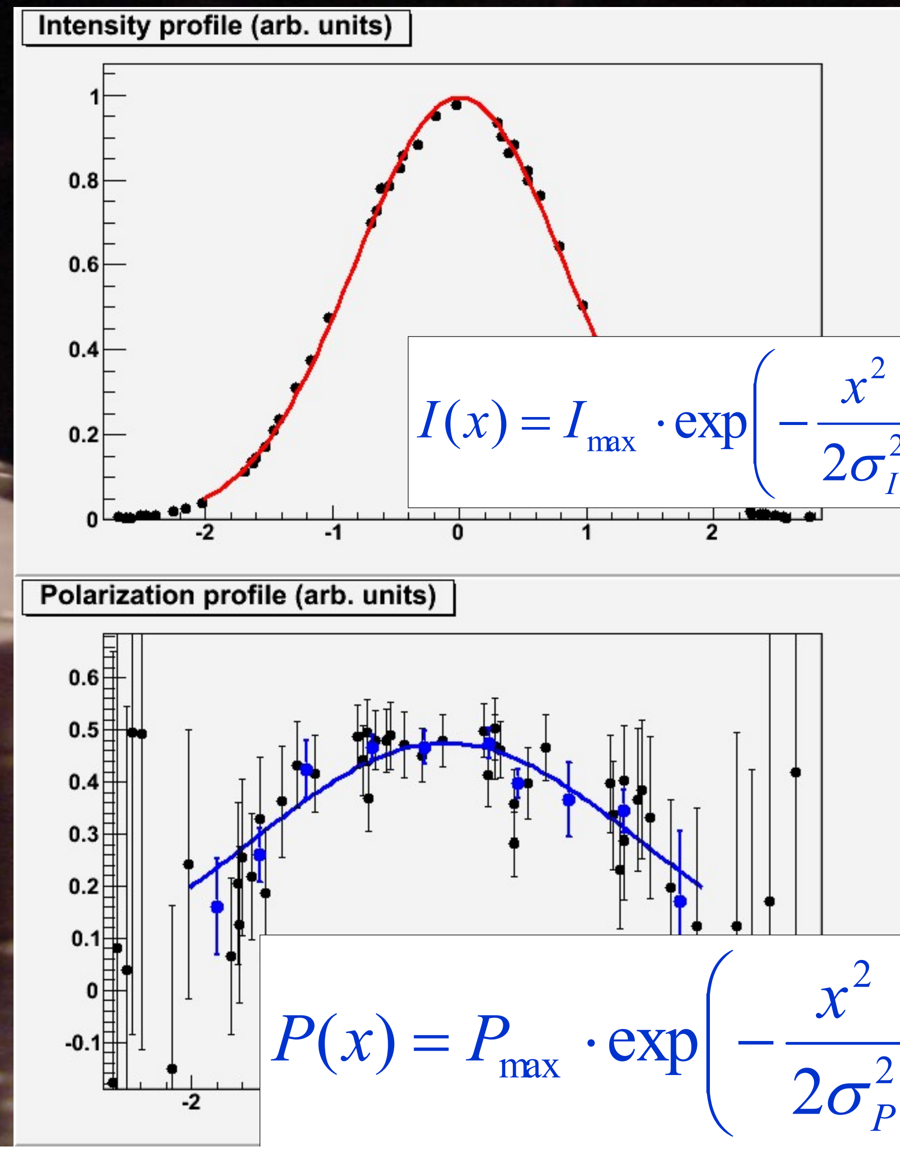
RHIC p-Carbon CNI polarimeter



New target motion mechanism





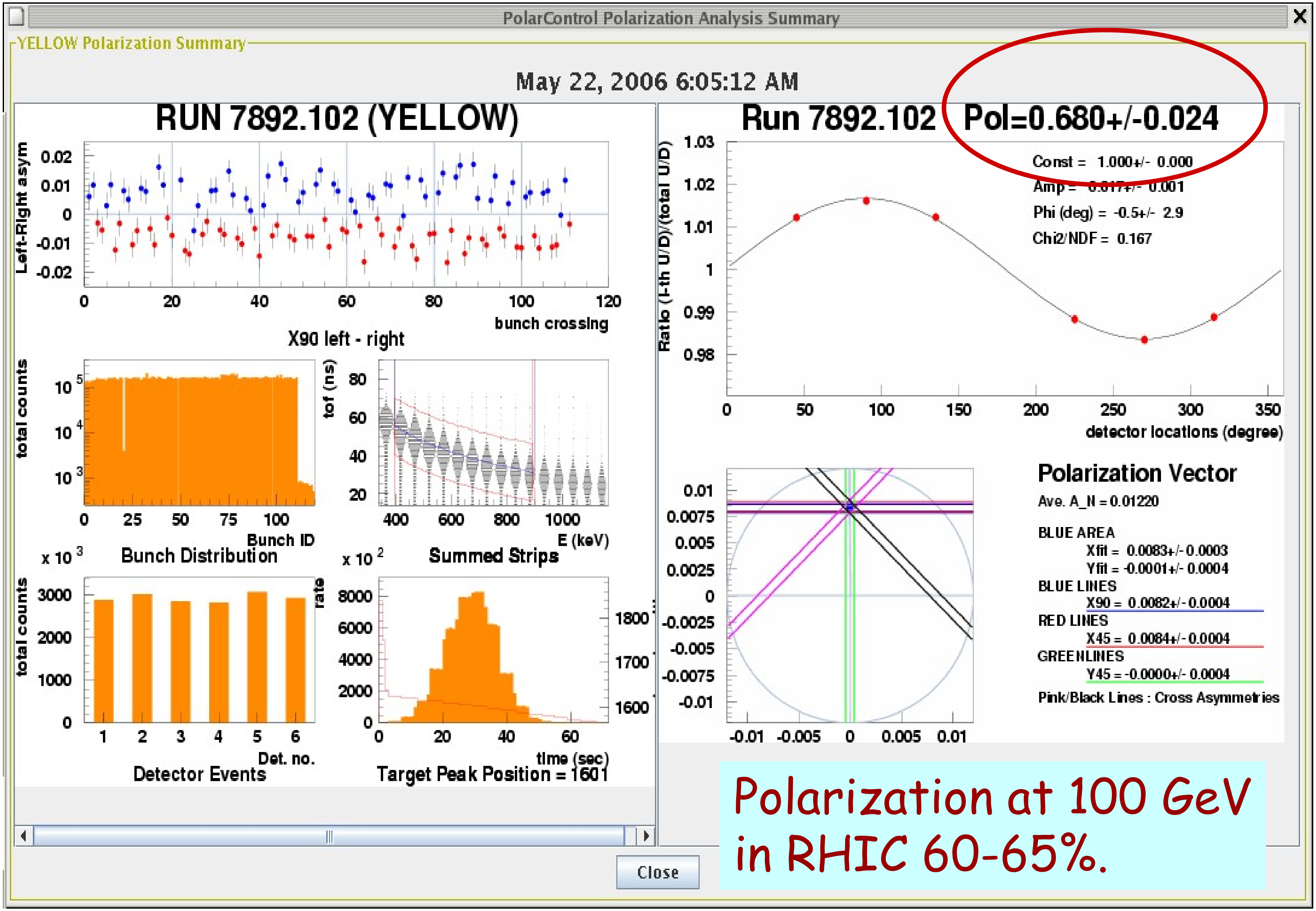


$$I(x) = I_{\max} \cdot \exp\left(-\frac{x^2}{2\sigma_I^2}\right)$$

$$P(x) = P_{\max} \cdot \exp\left(-\frac{x^2}{2\sigma_P^2}\right)$$

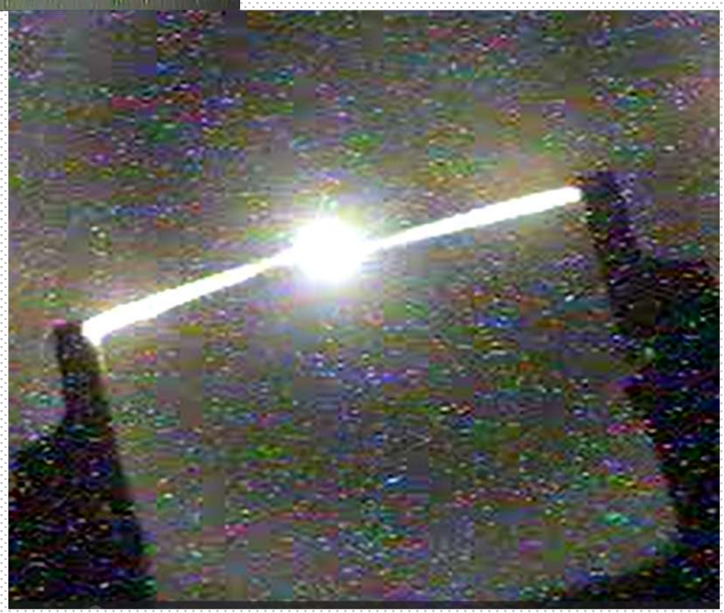
$$R = \frac{\sigma_I^2}{\sigma_P^2}$$

Polarization measurements in RHIC CNI polarimeters



Polarization at 100 GeV in RHIC 60-65%.

Carbon strip target deformation due to electrostatic interaction with the beam at 255 GeV.



CNI polarimetry

- p-Carbon polarimeters measure the direction of the polarization vector, its change in time and the polarization of each bunch.
- In combination with polarization measurements at the output of the linear accelerator and H-jet polarimeter, the use of CNI p-C will make it possible to restore a complete picture of the evolution of polarization during acceleration and monitor the value of proton polarization during experiments at the NICA collider.

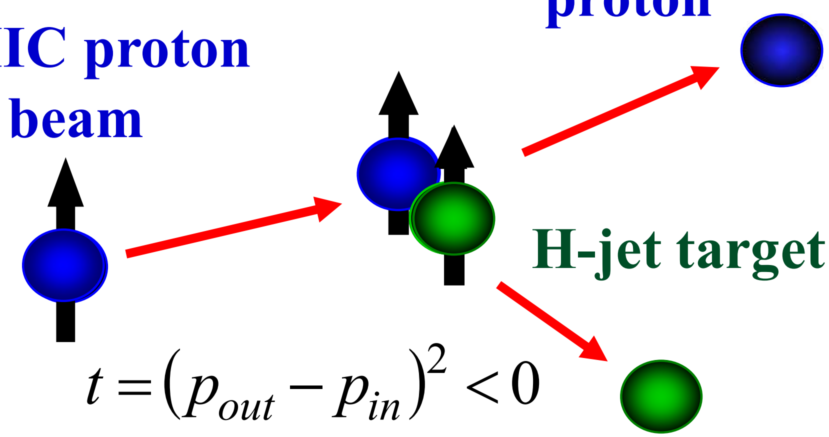
Absolute H-jet polarimeter

H-Jet polarimeter.

Elastic scattering: Interference between electromagnetic and hadronic amplitudes in the Coulumb-Nuclear Interference (CNI) region.

$$A_N \approx \mathrm{Im}\left(\phi_{SF}^{em}\phi_{NF}^{had} + \phi_{SF}^{had*}\phi_{NF}^{em}\right) \Big/ \left|\phi_{NF}^{had}\right|^2$$

$$A_N(t) = \boxed{-\frac{\varepsilon_{target}}{P_{target}}} = \boxed{\frac{\varepsilon_{beam}}{P_{beam}}}$$



$$t = \left(p_{out} - p_{in}\right)^2 < 0$$

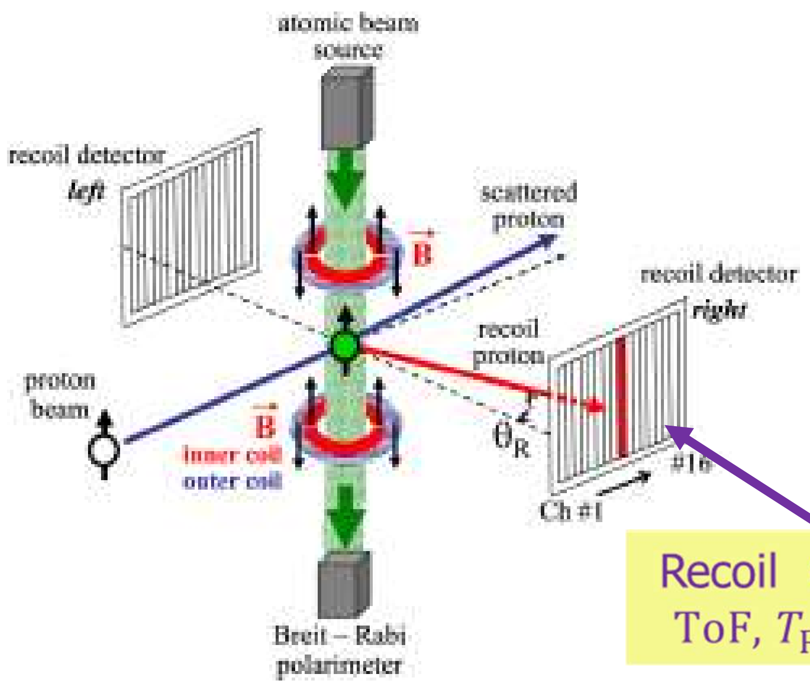
$$\boxed{\mathrm{P}_{\mathrm{beam}} = -\mathrm{P}_{\mathrm{target}} \frac{\varepsilon_{\mathrm{beam}}}{\varepsilon_{\mathrm{target}}}}$$

$$\frac{\Delta \mathrm{P}_{\mathrm{beam}}}{\mathrm{P}_{\mathrm{beam}}} \approx \frac{\Delta \mathrm{P}_{\mathrm{target}}}{\mathrm{P}_{\mathrm{target}}} \oplus \frac{\Delta\varepsilon_{\mathrm{target}}}{\varepsilon_{\mathrm{target}}} \oplus \frac{\Delta\varepsilon_{\mathrm{beam}}}{\varepsilon_{\mathrm{beam}}}$$ <5%

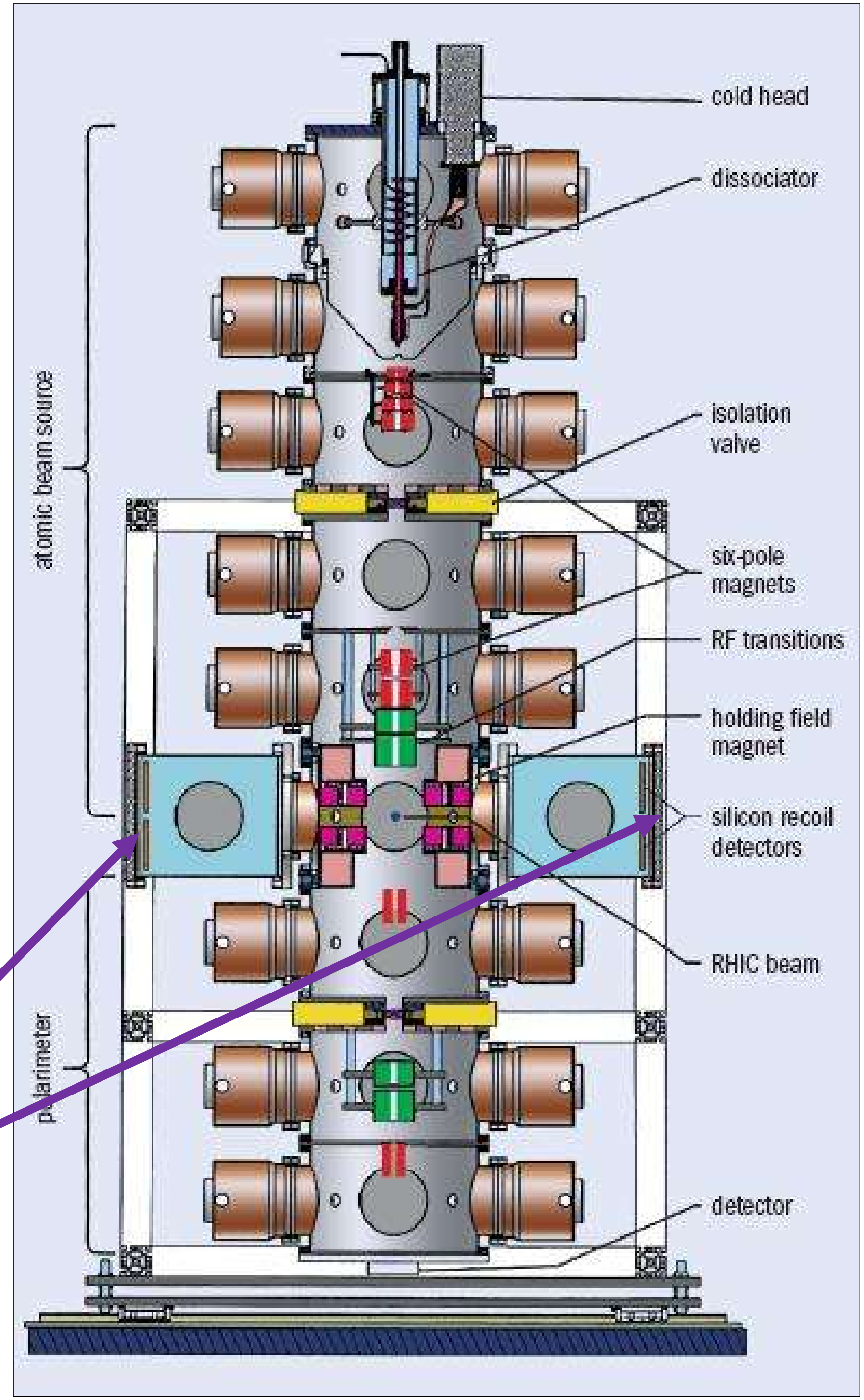
P_{target} is measured by Breit- Rabi Polarimeter

Absolute H-jet polarimeter

- The HJET polarimeter was commissioned in 2004.
- It was designed to measure absolute polarization of 24-250 GeV/c proton beams with systematic errors better than $\Delta P/P \leq 0.05$
- The atomic hydrogen polarization in the Jet is 95.7%
- Jet intensity 12.6×10^{16} atoms/sec
- Jet density 1.2×10^{12} atoms/cm^2
- The Jet polarization is flipped every 10 min.

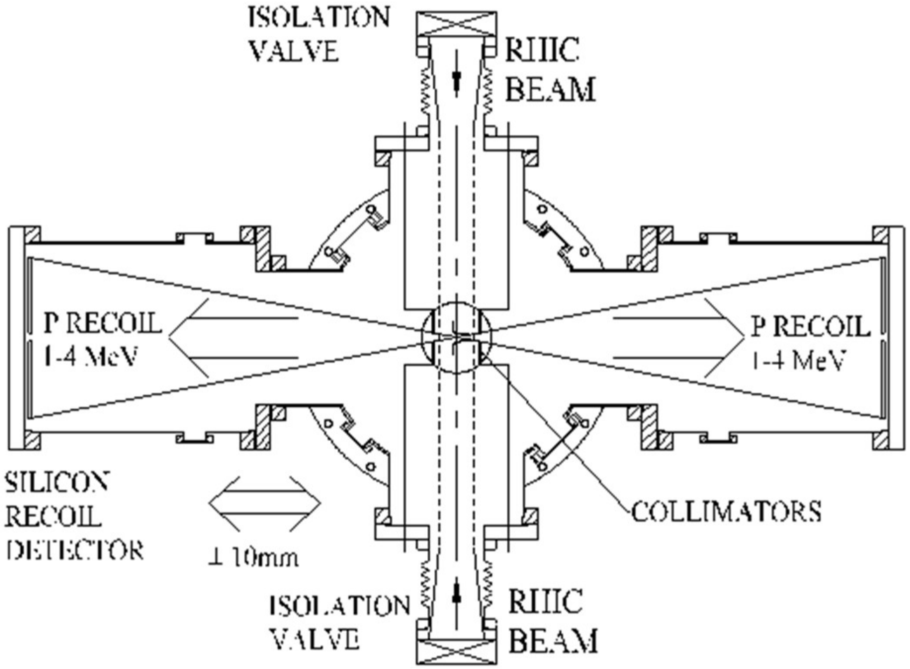


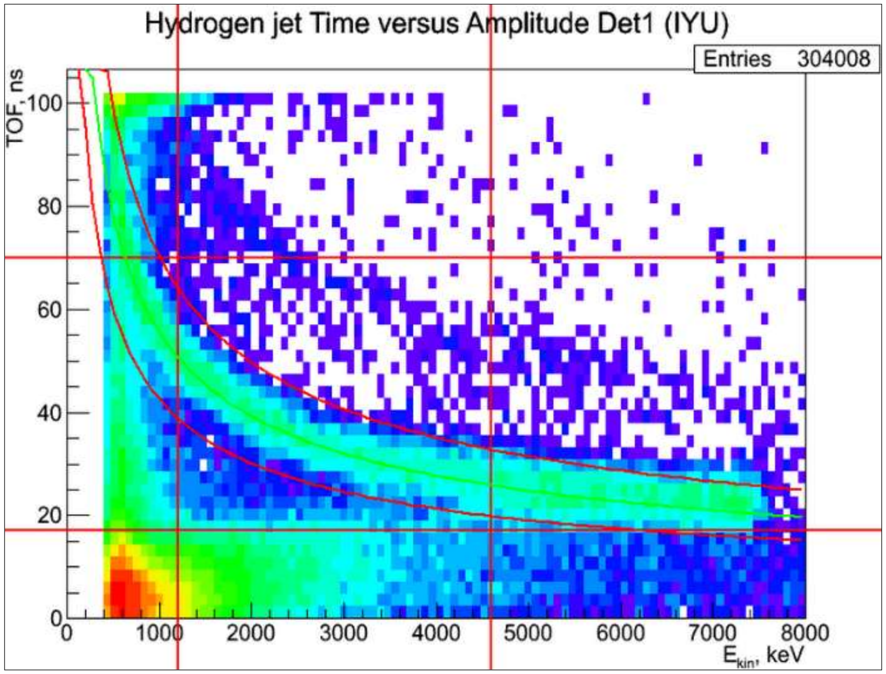
Recoil detectors
ToF, T_{REC}, θ_{REC}

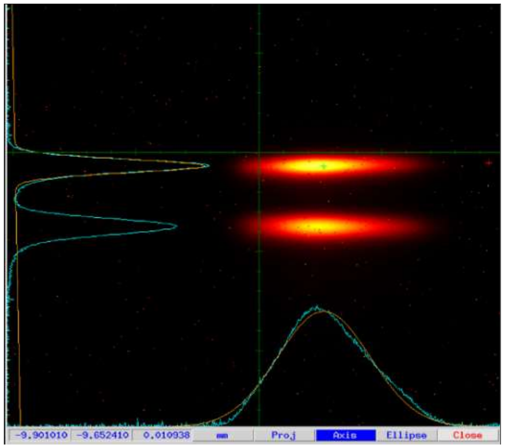


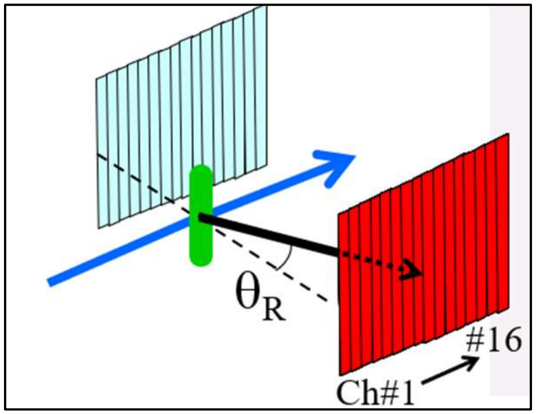
H-jet CNI polarimer

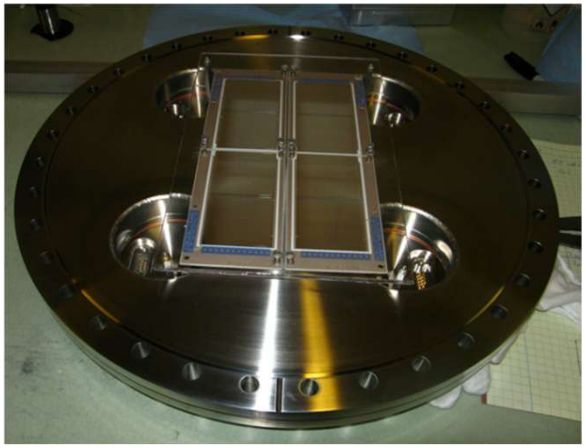
P-P Collision chamber



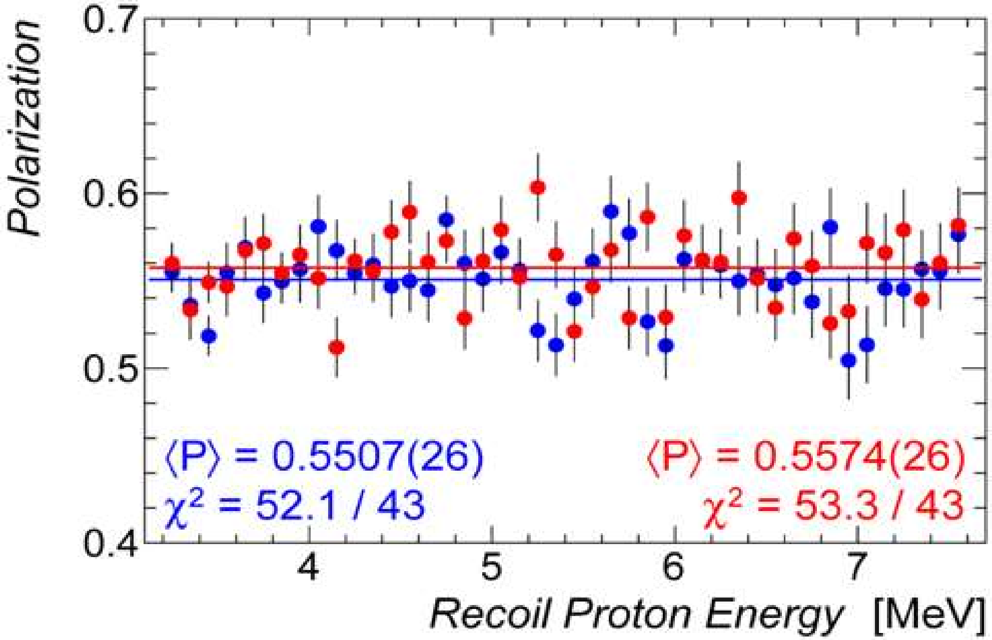








Results for minimum systematic error cuts



Systematic correction summary $\widetilde{\delta_{corr}}$

Source	Correction (%)	Error (%)
Long term stability		0.1
Jet Polarization		0.1
Molecular Hydrogen (1)	−0.03	0.03
Molecular Hydrogen (2)	−0.08	0.11
pA scattering		< 0.2
p+p→X+p	−0.15	0.15
Jet spin correlated noise		< 0.2
Total Systematic	**−0.26**	**< 0.37**

Strong elimination of the systematic error sources resulted in a ~0.7% correction to the $\delta P/P$. The residual systematic error of 0.4% does not look underestimated.

$$\langle P_{\text{jet}}\rangle = 0.957 \pm 0.001 \qquad \widetilde{\delta_{\text{corr}}} = (-0.3 \pm 0.4_{syst})\%$$

$$\boldsymbol{P_{jet}^{\text{eff}} = 0.955 \pm 0.004_{\text{syst}}}$$

Effective systematic error **0.6%**

$$\boldsymbol{A_N^{\text{eff}} = 0.03752 \times (1 \pm 0.004_{\text{syst}} \pm 0.004_{\text{stat}})}$$

$$\boldsymbol{A_N^{\text{eff}} = 0.03745 \times (1 \pm 0.004_{\text{syst}} \pm 0.004_{\text{stat}})}$$

A.Poblaguev, PSTP 2017

H-jet polarimeter at RHIC

- The polarized H-jet target thickness is $1.2 \cdot 10^{12}$ atoms/cm2 and with RHIC circulating current ~ 0.3 A (110 bunches $2 \cdot 10^{11}$ bunch intensity, $1.8 \cdot 10^{18}$ protons/s) the luminosity is $2.2 \cdot 10^{30}$ $cm^{-2}s^{-1}$
- "Point" like target is greatly beneficial for elastic event identification.
- The polarimeter Si-strip detectors covers all kinematic range of recoil protons (in CNI region) and about 20% solid angle which gives the statistical accuracy for one 8 hrs store about 2.0%.
- The proton polarization is mostly determined by the holding field magnetic field 1.2 kG and is equal to 95.5% (efficiency of the RF transitions are 99.88 % and the polarization dilution by the molecular gas contamination does not exceed 0.5%). At 1.5 kG polarization is 97%.

H-jet is the absolute high precision polarimeter !

- High (~4.5%) analyzing power in a wide energy range (23-255 GeV).
- High event rate due to high intensity (~300 mA) circulated beam current in the storage ring and high polarized H-jet thickness in the collision point.
- **Non-destructive.**
- **No scattering for recoil protons.- windowless.**
- **"Point" like target. Clean elastic scattering event identification.**
- Straightforward calibration with Breit-Rabi polarimeter.

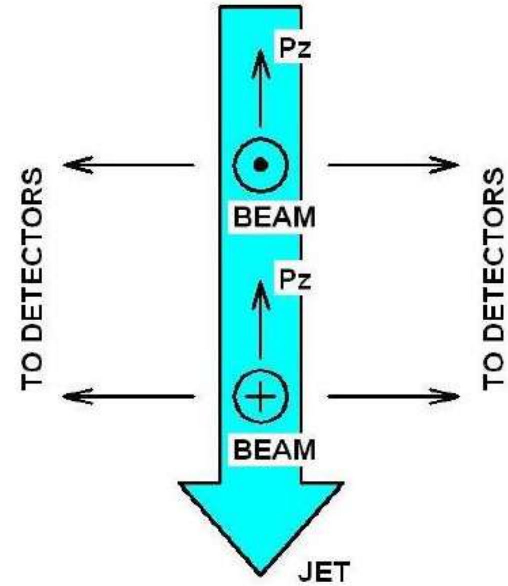
- Most of the false asymmetries are cancelled out in the ratio:

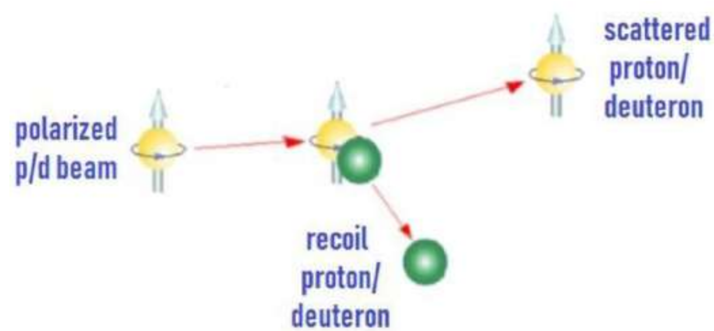
$$P_{beam} = (1/A) Beam_{asym} / Target_{asym}$$

A typical result for 8-hrs store: $\langle P \rangle = (\sim 56 \pm 2.0\ stat \pm 0.3 syst)$ %

Absolute Polarimeter (APol)

APol 3D view





CNI – H-jet polarimeter with the unpolarized hydrogen cluster-jet

- The accuracy achieved in determining $A_N(t)$ allows one to use a higher density unpolarized hydrogen jet target in a high precision absolute polarimeter.

- The unpolarized H-jet thickness of a 10^{14} -10^{15} H2/ cm2 can be produced by the cluster-jet technique, which was developed for the PANDA experiment at GSI[29].

- Considering a possibility to increase the recoil proton detectors solid angle, one can expect 1000 times higher elastic pp event rate compared to that in the RHIC HJET measurements.

- For such a polarimeter, only a 3 min. exposure is needed to determine the beam polarization with a statistical accuracy of stat P~ 1%, while the systematic uncertainty can be kept as low as $\Delta P/P$ ~1%.

- Therefore, an unpolarized jet can also provide accurate measurement of the polarization decay time and, with additional detectors at different azimuthal angles, the beams spin tilt.

Measurements of deuteron polarization in the Nuclotron and collider NICA at beam energies up to 13 GeV.

- The analyzing power for scattering in the coulomb-nuclear interference (CNI) region is proportional to the anomalous magnetic moment of the particle and for deuterons will be significantly less than for protons.
- Therefore, for measurements of the absolute value of polarization, the use of a CNI polarimeter with a jet of deuterium atoms polarized along the spin of the nucleus will be ineffective.
- For the deuteron beam energies below13 GeV in the Nuclotron and the NICA collider there is no resonance depolarization and polarization must be preserved.
- In this case, polarization measurements in the low-energy region, where the magnitude of the analyzing power is known with high ~ 2% accuracy, can be confidently extrapolated for higher energies.

- *The D-Carbon CNI polarimeters still can be used for polarization direction alignment.*

P-Carbon, 3He-Carbon analyzing power in CNI region

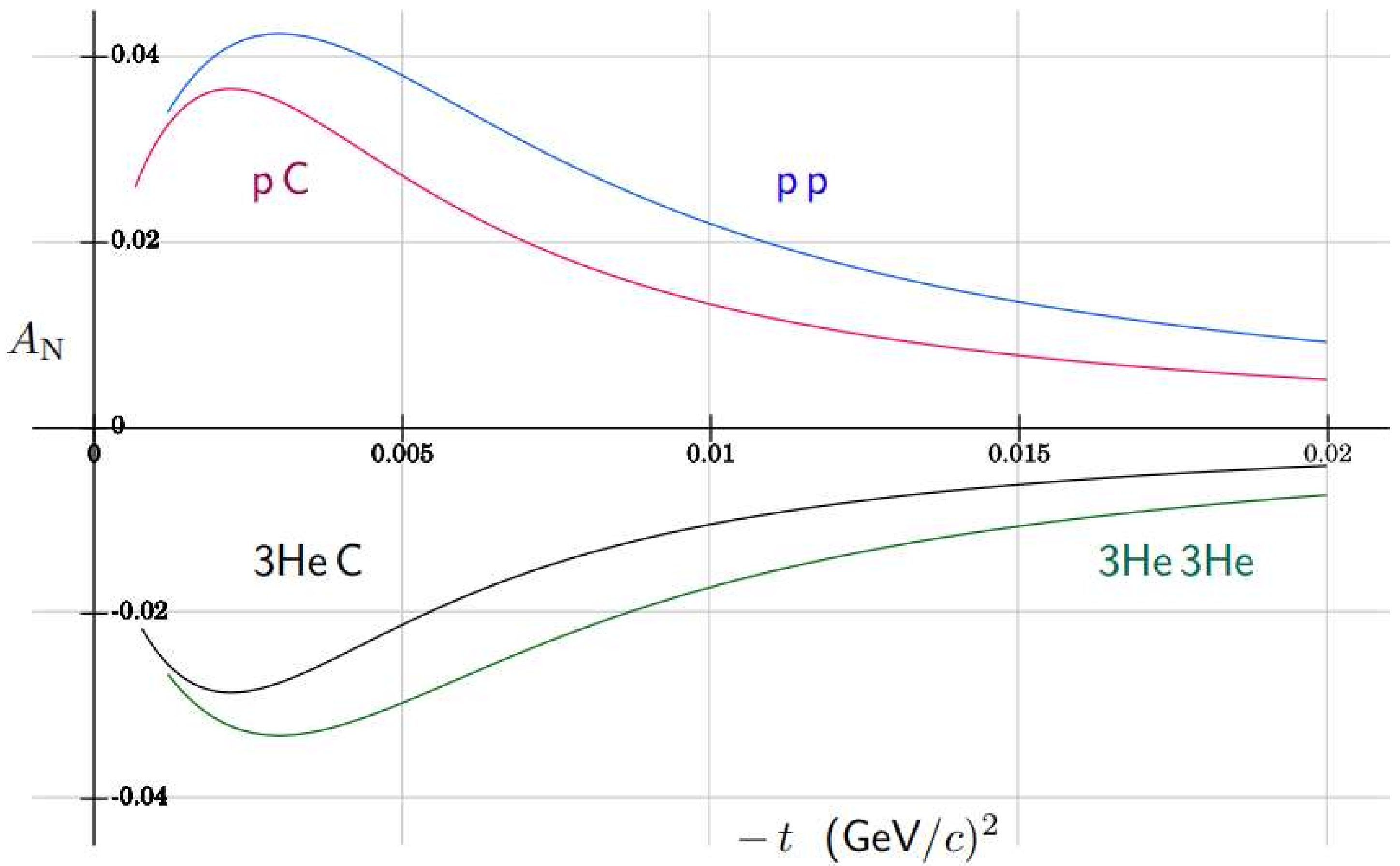


Figure 3: Analyzing power A_N versus invariant momentum transfer (-t) in $(\text{GeV}/c)^2$ for (1) p p and p h scattering, (2) p C scattering, (3) h C scattering, (4) h h and h p scattering

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Deuteron-Carbon CNI analyzing power

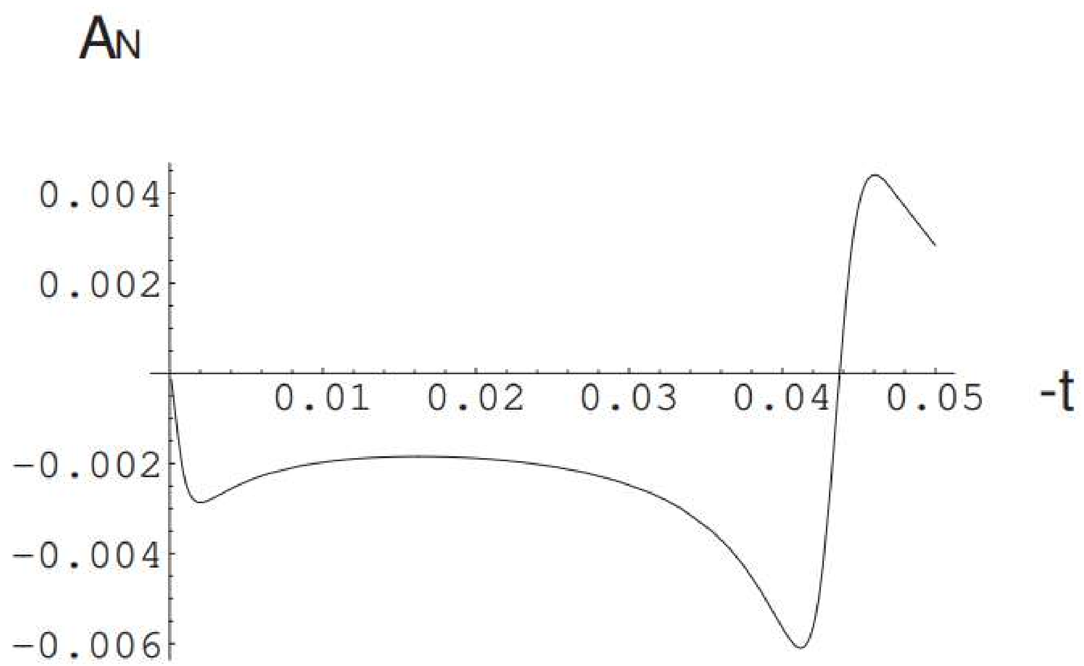

Figure 1: *The d-C analyzing power with zero hadronic flip amplitude* $\tau = 0$.

We expect the increase of the D-Carbon analyzing power, similar to p-Carbon at lower energies.
This can be studied in the Nuclotron and also it might be a good exercise for the theoreticians.

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CNI polarimetry

- These polarimeters also measure the direction of the polarization vector, its change in time and the polarization of each bunch. In combination with polarization measurements at the output of the linear accelerator and APol, the use of CNI p-C will make it possible to restore a complete picture of the evolution of polarization during acceleration and monitor the value of proton polarization during experiments at the NICA collider.

- The analyzing power for elastic scattering decreases with increasing energy. With a maximum NICA energy of 13.0 GeV and $|t|$ = 0.3 (GeV/c)2, the analyzing power was measured with high accuracy and is still high enough 4.66±0.26% for efficient polarimetry [18]. Polyethylene targets can be used only at a low intensity of the beam < $5 \cdot 10^9$ particles/bunches and a small number of bunches.

- For measurements at the full design intensity, it is proposed to use a cluster jet hydrogen target with a thickness of ~10^{15} H2/cm2 , which will allow obtaining of a high counting rate and an absolute polarization measurement accuracy better than 5%, by using analyzing power values measured in the polarimeter with a polarized hydrogen jet.