Relative Polarization Measurements of Proton Beams Using Thin Carbon Targets at RHIC

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Recent RHIC Performance

- Each year RHIC has had steady luminosity improvements

- **2015**
  - $P = 55.8\%$ at $\sqrt{s} = 100$ GeV
  - $P = 55.2\%$

- **2013**
  - $P = 52.3\%$ at $\sqrt{s} = 255$ GeV
  - $P = 54.4\%$

- **2012**
  - $P = 57.0\%$ at $\sqrt{s} = 100$ GeV
  - $P = 55.8\%$
  - $P = 49.9\%$ at $\sqrt{s} = 255$ GeV
  - $P = 52.2\%$

- **2011**
  - $P = 47.0\%$ at $\sqrt{s} = 250$ GeV
  - $P = 52.2\%$

- **2009**
  - $P = 55.6\%$ at $\sqrt{s} = 100$ GeV
  - $P = 54.0\%$
  - $P = 37.8\%$ at $\sqrt{s} = 250$ GeV
  - $P = 38.9\%$
RHIC Polarimetry

Polarized hydrogen Jet Polarimeter (HJet)
Source of absolute polarization (normalization of other polarimeters)
Slow (low rates $\Rightarrow$ needs looong time to get precise measurements)

Proton-Carbon Polarimeter (pC) @ RHIC and AGS
Very fast $\Rightarrow$ main polarization monitoring tool
Measures polarization lifetime and profile (polarization is higher in beam center)
Needs to be normalized to HJet

Local Polarimeters (in PHENIX and STAR experiments)
Defines spin direction in experimental area
Needs to be normalized to HJet

All of these systems are necessary for the proton beam polarization measurements and monitoring
CNI Polarimetry at RHIC

- The maximum analyzing power is expected in Coulomb-Nuclear Interference (CNI) region

\[ \frac{N}{N_L + N_R} = \frac{N_L - N_R}{N_L + N_R} \]

Theoretical results with hadronic spin flip and without hadronic spin flip.

- Measured Polarization \( P_{\text{beam}} = \frac{N}{A_{pC}^N} \)

- The analyzing power, \( A_N \), must be known
Polarized Proton Beams

Carbon polarimeters
Two per ring
Fast measurement (3-4 measurements per RHIC store)

Beam polarization profile
Polarization decay (time dependence)

Each Polarimeter uses six vertical and six horizontal ultra thin carbon targets

Hydrogen jet polarimeter
Polarized target
Continuous operation
\( \sigma \approx 5 - 8\% \) per fill

Normalization
Two $\alpha$ sources, Am(5.5 MeV) and Gd (3.3), used for energy calibration of detector

- Detectors are $\approx 20$ cm from the beam in a vacuum chamber
- 2 mm good gain stability, coarse segmentation
- 1 mm poor gain stability (but monitored), fine segmentation
Hardware improvements in 2015

- Again use 2mm Si-detectors because of very good gain stability

- new target holders
  - EM simulation (J. Kewisch) showed beam charge induced high EM fields at target → frame attachment (lightning rod)
  - high fields ⇒ high current in target ⇒ heating
  - Such fins installed for 32 of 48 targets in 4 pC polarimeters (no room for fins other targets, hit chamber wall)

![Target ribbon inside](image)

E.C. Aschenauer
The effective energy losses $E_{\text{loss}}$ and time offset $t_0$ are determined from the kinematical fit to the banana-like band.

Carbon Events are selected within a Time-Energy window, $400 < T < 900$ keV, optimized for minimal background.

$$E_{\text{kin}} = E_{\text{meas}} + E_{\text{loss}} = \frac{1}{2} M \times \frac{L^2}{(t_{\text{meas}} + t_0)^2}$$
**Beam Polarization Profile**

\[ P = \frac{P(x, y) I(x, y) dx dy}{I(x, y) dx dy} \]

\[ P_{\text{sweep}} = P \]

\[ P_{\text{coll}} = \frac{P(x, y) I_1(x, y) I_2(x, y) dx dy}{I_1(x, y) I_2(x, y) dx dy} \]
Gaussian distributions are used to describe the polarization and intensity profiles:

\[ P = P_{\text{max}} e^{-\frac{x^2}{s_P^2}} \]
\[ I = I_{\text{max}} e^{-\frac{x^2}{s_I^2}} \]

Polarization Profile is characterized by:

- Centeral Value \( P \)
- Profile Parameter \( R \)

\[ R = \frac{s_I^2}{s_P^2} \]

\[ P = P_{\text{max}} \left( \frac{I}{I_{\text{max}}} \right)^R \]
Polarization Loss in Fill

- During beam acceleration, polarization is lost.
- Polarization decreases while $R$ increases.
- Losses consistent with beam profile broadening.
- RHIC experiments can use the $\frac{dP}{dt}$ and $P_0$ to reweight individual fills according to their recorded luminosity.
Polarization Loss in a Fill for Run 15

Linear approximation for polarization $P$ and profile $R$ in a fill:

$$P = P_0 + \frac{dP}{dt} t$$

$$R = R_0 + \frac{dR}{dt} t$$

- Average change in $P$ and $R$ is:

$$\frac{dP}{dt} \sim 1.00 \pm 0.03\% \text{ per hour}$$

$$\frac{dR}{dt} \sim +0.012 \pm 0.002 \text{ per hour}$$
Measuring the Target Thickness

- Scattered carbons have a uniform azimuthal angle, \( \phi \), distribution:
  \[
  \frac{dN}{d\phi} = 1 + P A_N \cos(\phi)
  \]

- Polar scattering angle very narrow range \( \theta \sim 90^\circ \):
  - \( 4 < \theta < 6 \) mrad for \( 0.4 < T < 0.9 \) MeV

- Finite target thickness results in Multiple Coulomb Scattering (MCS) smearing the \( \theta \) distribution:

\[
RMS = \frac{K \sqrt{L_{\text{target}}}}{E_{\text{kin}}}
\]

\( pC \rightarrow pC \ \theta \ vs. \ E_{\text{kin}} \)
Effects on Analyzing Power

- The p-Carbon scattering $A_N(T)$ falls a function of $T$
- Detectors measure in the window of (solid lines) $0.4 < T < 0.9$ MeV
- The effective analyzing power:
  $$A_N \mu \frac{d}{dT}$$
- Carbonons at higher $T$ (dotted lines) are shifted down to the measured $T$ window
- These carbons have a smaller effective $A_N$

Thicker Targets Lead to a lower effective Analyzing Power
Detectors Used

- The top 45° detectors (1 & 6) are 1 mm detectors segmented along the beam line.
- Strip polar $\Delta \theta \approx 5$ mrad.
- # hits/channel distribution provides information on:
  - Centroid => longitudinal Z position of target
  - Width => amount of MCS through target

Ultra thin Carbon ribbon Target (5 $\mu$g/cm²)
Si strip detectors (TOF, $E_C$)

12 x 1 mm strips
Toy Monte Carlo Model

- Exponential distribution in scattered carbon energy
- $E \leftrightarrow \theta$ scattering angle dependence (kinematics)
- Passage of scattered carbon through varying target thickness $0 < L < L_{\text{max}}$ with:
  - Small angle MCS in target material
  - $dE/dx$ carbon energy loss
- 19.2 mm distance from target to detector
Hit Distributions and Fits

- **Fit Parameters:**
  - $N_{\text{tot}}$: total number of events (normalization)
  - $Z_0$: target longitudinal position
  - $L_{\text{max}}$: target -> detector thickness
  - Fbkg: flat background

![Graphs showing hit distributions with fit parameters]
Run 15 History for $L_{\text{max}}$

- $L_{\text{max}}$ is a property of the target
- MCS parameters are uncertain for these low energies, adjusted $L_{\text{max}} \rightarrow 2L_{\text{max}}$ for model comparisons
- $L_{\text{max}}$ increases with target use? Why?
- Target manufactured at $50 \pm 4$ nm, but we see some measurements $< 30$ nm.

Sept 14, 2015

PSTP2015
$A_N$ vs. $L_{max}$

- Averaged over all polarimeters (black), and each individual polarimeter:
- Run 13 (255 GeV) and Run 15 (100 GeV) display the same downward trend, but different slopes.
- $A_N$ has a 10% change over 100 nm range in target thickness.
- Shifted Energy window describes data well!

$A_N$ has a 10% change over 100 nm range in target thickness. Shifted Energy window describes data well!
Spin tilt @ pC Polarimeters

• 3 180° detector pairs:
  • det 1+4, 2+5, 3+6

• Measure 3 separate asymmetries:
  – \( \varepsilon_{25} = A_N P_Y \)
  – \( \varepsilon_{14} = A_N P_V \)
  – \( \varepsilon_{36} = A_N P_U \)

• All detector pairs measure the same beam and polarization vector \( P \), which provides two measures of \( \varepsilon_Y = A_N P_Y \) where \( P_Y = 1/\sqrt{2}(P_U + P_V) \):
  – \( \varepsilon_{Y90} = \varepsilon_{25} \)
  – \( \varepsilon_{Y45} = 1/\sqrt{2}(\varepsilon_{14} + \varepsilon_{36}) \)

• H-jet polarimeter can only measure the y components
• Thanks to the 45° detectors the pC polarimeter can measure both \( P_X \) and \( P_Y \)
**tan(φ) from 45° detectors**

Using 45° detectors → measure $P_x$, $P_y$ and spin tilt from vertical

\[
\tan \phi = \frac{P_x}{P_y} = \left(\frac{P_u - P_v}{P_u + P_v}\right) = \frac{(\varepsilon_{36} - \varepsilon_{14})}{(\varepsilon_{36} + \varepsilon_{14})}
\]

independent of scale of $A_N$

**2013 Results:**

<table>
<thead>
<tr>
<th>Year</th>
<th>Energy (GeV)</th>
<th>Blue</th>
<th>Yellow</th>
<th>Injection</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>250</td>
<td>-2.9</td>
<td>-1.07</td>
<td>0.92</td>
</tr>
<tr>
<td>2012</td>
<td>100</td>
<td>3.05</td>
<td>-0.97</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>255</td>
<td>13.81</td>
<td>-6.49</td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>255</td>
<td>16.14</td>
<td>-9.01</td>
<td>1.25</td>
</tr>
<tr>
<td>2015</td>
<td>100 (1)</td>
<td>3.76</td>
<td>1.92</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100 (2)</td>
<td>3.72</td>
<td>1.27</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100 (3)</td>
<td>4.86</td>
<td>3.19</td>
<td></td>
</tr>
</tbody>
</table>

Many additional studies in 2015 (3) to understand polarization lifetime

**In geographical coordinates:**

@ pC polarimeter

@ store both Blue and Yellow spin vectors tilted toward RHIC ring center

What about H-Jet
Spin vector tilt @ IP12=H-jet

- H-jet polarimeter is at IP12: has only 90° horizontal detectors, measures $\epsilon_Y \propto P_Y$
- The H-jet measurements normalize scale of pC measurements (determine pC $A_N$)
- To date we have assumed H-jet measures polarization magnitude $|P|$
- If there is a spin tilt $\phi \neq 0$ @ IP12 we have a $|P|$ scale shift of $\cos\phi$
  - e.g. Yel @ store: $\phi = -9^\circ \quad \cos\phi = 0.99 \quad$ 1% scale shift
  - Blu @ store: $\phi = +16^\circ \quad \cos\phi = 0.96 \quad$ 4% scale shift

- A 4% shift is significant, need to account for in polarization measurements...
  has been done for the final 2013 polarization numbers

Francois Meot did show through simulation spin angle at H-Jet is identical to the one at pC

Experiments measure the spin tilts through the ZDC asymmetries
Summary

• p-Carbon polarimeters at RHIC have consistently performed well in 2011, 2012, 2013, and 2015
• They provide information on the beam polarization profile and measures the polarization loss during a RHIC store
• Target lifetime has improved thanks to the new fin design of the target holder
• Studies to determine the amount of material in the flight path to detectors are ongoing and show promising results.
• Potential to precisely measure p-Carbon $A_N$ at very high beam energies
Back-Up
\(<L_{\text{max}}\) in Sweep

- The target twists, turns, etc. as it enters the beam
- The value of \(L_{\text{max}}\) varies as target sweeps across the beam
- Rate averaged \(L_{\text{max}}\) is used
Average Polarization in 2015 at $E_{\text{beam}} = 100$ GeV

**Blue Beam, 100 GeV** $\langle P \rangle \approx 53\%$

![Graph showing polarization data for the Blue Beam.]

**Yellow Beam, 100 GeV** $\langle P \rangle \approx 57\%$

![Graph showing polarization data for the Yellow Beam.]

<table>
<thead>
<tr>
<th>$\chi^2$ / ndf</th>
<th>456.5 / 148</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prob</td>
<td>3.535e-33</td>
</tr>
<tr>
<td>$p_0$</td>
<td>53.03 ± 0.2731</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>$\chi^2$ / ndf</th>
<th>305.5 / 148</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prob</td>
<td>5.281e-13</td>
</tr>
<tr>
<td>$p_0$</td>
<td>57.45 ± 0.2783</td>
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</table>
Spin tilt @ pC Polarimeters

Square root (cross ratio) formula

If detectors (L,R), 180° apart:
- Accept detector acceptances \( a_L, a_R \)
- Summed to up/down beam
- Accept up/down luminosity
- Polarization along beam polarization asymmetry \( \epsilon \) prop.

pC polarim.: 3 detector pairs

- 3 180° detector pairs, det.1+4, 2+5, 3+6:
  - Measure 3 sets of asymmetries:
    \[
    \epsilon_{25} = A_N P_Y , \lambda_{25} , \alpha_{25} \\
    \epsilon_{14} = A_N P_V , \lambda_{14} , \alpha_{14} \\
    \epsilon_{36} = A_N P_U , \lambda_{36} , \alpha_{36}
    \]

Cross checks:

- All detector pairs measure same beam, lumi asym. \( \lambda \)
  - compare \( \lambda_{14}, \lambda_{25}, \lambda_{36} \) : agree within stat. uncert. (extra slide)

- All detector pairs measure same beam, polarization vector \( P \)
  - two measures of \( \epsilon_Y = A_N P_Y \) using \( P_Y = 1/\sqrt{2}(P_V + P_U) \)
    - from 90° det. 2+5: \( \epsilon_{Y90} = \epsilon_{25} \) (vertical targets only)
    - from 45° det. 1+4, 3+6: \( \epsilon_{Y45} = 1/\sqrt{2}(\epsilon_{14} + \epsilon_{36}) \)
    - compare \( \epsilon_{Y90}, \epsilon_{Y45} \) : agree within stat. uncert. (extra slide)

Also: \( A_N \sim \) same all detector pairs