PROCEEDINGS OF SCIENCE

Polarization measurements and absolute polarization values evolution during proton beam acceleration in RHIC accelerator complex

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Abstract. The knowledge of absolute polarization measurements at different beam energies is very important for understanding of the polarization losses during acceleration and transport in the RHIC accelerator chain: Source-Linac-Booster-AGS-RHIC. In the RHIC accelerator complex there are two absolute proton polarimeters: the elastic proton-Carbon polarimeter at 200 MeV beam energy and the CNI H-jet polarimeter at 24-255 GeV in the RHIC ring. The polarization transport simulations show that depolarization occurs at the edge of the beam and that the polarization of the beam core at the center of the 2-dimensional beam intensity profile should be preserved during acceleration. Polarization profile measurements by the scanning p-Carbon CNI polarimeters in the AGS and RHIC provide experimental data that support these expectations. The combination of polarization transport simulation and absolute polarization measurements tools at AGS injection and RHIC store energies provides complimentary information on polarization losses along the RHIC accelerator chain. In addition, an estimate for the upper limit on polarization in collisions is calculated from the absolute polarization measurements at beam energies 200 MeV, 100 GeV and 255 GeV.

XVth International Workshop on Polarized Sources, Targets, and Polarimetry
September 9-13, 2013
Charlottesville, Virginia, USA

1 Speaker

PoS(PSTP 2013)056

1. Introduction

RHIC is the first collider where the "Siberian snake" technique was successfully implemented to suppress the resonance depolarization during beam acceleration in AGS and RHIC [1]. Two partial helical snakes in AGS and two full (180 deg) helical snakes in each RHIC ring are used for polarization preservation during acceleration and beam storage time.

In the RHIC complex, there are two absolute proton polarimeters: the elastic proton-Carbon polarimeter at beam energy 200 MeV [2] and the CNI proton-proton H-jet polarimeter at the RHIC store energies of 100 and 255 GeV [3]. The polarization of the 200 MeV beam is 80-84% and was measured with an accuracy of better than 0.5%. The H-jet polarimeter measures the average polarization over the whole beam intensity profile. The averaged polarization of 63±4.4% was measured at injection beam energy 24 GeV, 61.1±0.7% at beam energy 100 GeV and 50±0.6% at energy of 255 GeV (Run-2012, Blue ring). This means that most of the polarization losses occur in AGS and in RHIC during acceleration from 100 to 255 GeV. The polarization transport simulations show that depolarization occurs at the edge of the beam and polarization of the beam core (center of the beam intensity profile) should be preserved during acceleration. Polarization distribution across the beam intensity profile (beam polarization profile) is measured by the scanning p-Carbon CNI polarimeters in AGS and RHIC [4, 5]. These measurements produce complimentary information to the H-jet polarimeter on polarization losses along the accelerator chain. The knowledge of polarization profiles of both beams are also required for calculation of the polarization values for colliding beams, which are used for the normalization of experimental spin asymmetries [5, 6].

2. Polarization and polarization profile measurements in AGS and RHIC

As shown experimentally, the beam intensity and polarization profiles measured with the p-C polarimeters in AGS and RHIC can be well approximated by Gaussian distributions [5,7]. The basic framework for polarization profile analysis was introduced in A. Bazilevsky and W. Fischer papers [5,6]. For polarization profile characterization, parameters R_H for horizontal profiles and R_V for vertical profiles were introduced as follows:

$$R_H = \frac{\sigma_{x,I}^2}{\sigma_{x,P}^2} \qquad\qquad R_V = \frac{\sigma_{y,I}^2}{\sigma_{y,P}^2}$$

where $\sigma_{x,\,I}$, $\sigma_{x,\,P}$, $\sigma_{y,\,I}$, $\sigma_{y,\,P}$ are corresponding rms widths of Gaussian distributions for intensity and polarization profiles. Then an average beam polarization (as measured by the H-jet polarimeter) $<P>$ can be calculated:

$$\langle P \rangle = \frac{P_0}{(1+R_H)(1+R_V)} \qquad (1)$$

where P_0 is the maximum polarization of the beam core (at zero betatron oscillation amplitudes in both vertical and horizontal directions) [6].

The polarization transport simulations show that depolarization occurs at the edge of the beam and polarization of the beam core P_0 should be preserved during acceleration. The experimental data in AGS support these expectations [8]. The above formula provides the relation between average polarization $\langle P \rangle$ and polarization profiles evolution along the accelerator chain. The absolute values of the average beam polarization were measured by the H-jet polarimeter during the physics stores at beam energies of 100 GeV, 250 GeV and 255 GeV. The H-jet atomic beam size (FWHM~ 6 mm) is much larger than the accelerated proton beam size (FWHM ~ 0.3-0.5 mm) therefore the H-jet polarimeter measures the average beam polarization $\langle P \rangle = P_{jet}$. The H-jet measurements at the RHIC injection energy are not routinely available and absolute measurements and polarization monitoring is based on p-Carbon CNI polarimeter polarization (and polarization profile) measurements in AGS and RHIC injection, which were normalized by the H-jet measurements.

There is no depolarization during beam transport and acceleration in the Linac from the source to the 200 MeV polarimeter and Booster injection. The polarization profile measurements in the 200 MeV polarimeter produced R-values consistent with zero and the average beam polarization is equal to P_0 ~80-84% depending on beam intensity [9]. The polarization direction in the Linac and at the Booster injection is vertical (as measured using the 200 MeV polarimeter), which is tuned precisely by the polarization rotator system before injection into the Linac. The polarization profile at AGS injection energy is flat, which is consistent with no losses in Booster after the careful tuning of the orbit harmonics. In AGS the use of two partial helical snakes and Jump Quads greatly improved the polarization preservation, but still there are some losses depending on beam emittance. The non-flat polarization profiles at AGS flattop energy have been measured by CNI polarimeters in AGS and at injection in RHIC. The results of the polarization and polarization profile measurements at different beam energies are presented in **Table I**.

Beam energy, GeV	100	100	255	255
Blue (**B**), Yellow (**Y**) ring	**B**	**Y**	**B**	**Y**
P_{jet}, %	61.2±0.71	55.8± 0.8	57.1±0.9	57.7±0.9
R_V~R_H	0.100±0.07	0.158±0.022	0.105±0.023	0.103±0.022
P_0, %	74.1±1.2	74.8±2.5	69.7±2.9	70.2±2.8
$P_{0,max}$, %	75.6±0.5	78.2±0.5	77.6±0.5	80.2±0.5
P_{coll}, %	64.1±0.8	60.0±1.0	60.0±1.2	60.5±1.1

The 255 GeV data set was taken during the best running period in Run-2013 ("golden fills" 17416-17440, see figure 1), and the set of 100 GeV data are from Run-2012. The maximum possible beam core polarization $P_{0,max}$ in RHIC is the source polarization corrected for the polarization direction mismatch in AGS and RHIC. In Run-2012 source polarization was 79.3% and after the source upgrade in Run-2013 polarization increased to 81.3% [9]. For the Yellow ring this factor is equal to 0.991 and for the Blue ring it is equal to 0.958, therefore $P_{0,max}$ numbers in the Table are correspondingly smaller than the source polarization. The calculated experimental P_0 numbers in Table I, using formula (1) from P_{jet} and R-values, are somewhat lower than the expected $P_{0,max}$ values, especially for the 255 GeV data set. This might be an indication of some other mechanisms of polarization losses, or possible systematic errors in polarization profile R-values measurements.

Polarization for colliding beams: P_{coll}, the luminosity-weighted average over the polarization distributions, was also calculated using R_H and R_V values [6]:

$$P_{coll} = P_{jet}\sqrt{\frac{(1+R_V)(1+R_H)}{(1+\frac{1}{2}R_V)(1+\frac{1}{2}R_H)}} \qquad (2)$$

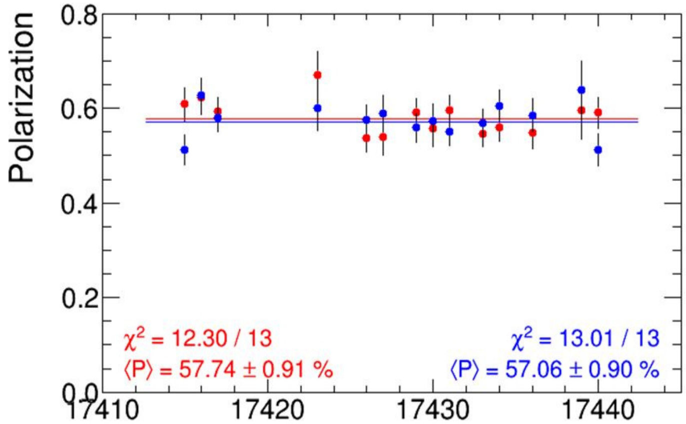

Figure 1: H-jet polarization measurement in Run-2013

3. Systematic errors of polarization profile measurements

The target ladder motion due to target looseness does not accurately define the carbon target position (in the p-Carbon CNI polarimeter during the scan). It is very difficult to control the thin target straightness during installation. Also after the exposure by the proton beam the carbon targets expand and become loose. The electrostatic interaction from the proton beam attracts loose carbon strips changing their position. These effects are stronger at higher beam intensities. Most beam intensity profile measurements are strongly corrupted by these uncontrolled target motions. An analysis technique was developed, which uses a counting rate (instead of target position) as a signature of target position in the beam. The corresponding polarization measurements vs. counting rate are also used for polarization profile measurements [5]. This technique works well if the amount of target material exposed to the beam is not changing during the scan. The polarization profile numbers which are presented in Table I were calculated using these assumptions.

During Run 2012 an increased target loss rate was observed. To investigate this problem a video camera was installed to visualize the target motion during the scan. Strong target deformations were recorded (see Fig. 2).

Figure 2. Polarimeter target deformation due to electrostatic interaction with the proton beam. Left picture-measurement at injection energy; Right- at 255 GeV beam energy

These pictures clearly show that due to the target-beam interaction the excess length of loose targets is attracted into the beam. This changes the amount of target material interacting with the beam. Larger numbers of events are coming from the beam core (with the higher polarization) due to target deformation. These effects corrupt the polarization profile measurements and reduce the calculated polarization profile R-values and most important the P_{coll} values, which is used for experimental spin asymmetries normalization. It is not clear how to make a correction for this deformation because it is also changing in time. Presently the measured R-values and correspondingly P_{coll} numbers calculated using these R-values could be only considered as a lower limit on R and P_{coll}.

4. Estimate of upper limit for the P_{coll} from the H-jet polarization measurements

The measured values of polarization profile factors in vertical and horizontal planes are very close to each other (probably due to coupling between horizontal and vertical plane motions): $R_H \sim R_V = R$. In this approximation, formula (1) can be simplified:

$$R_V = R_H = R \Rightarrow 1 + R = \sqrt{\frac{P_0}{P_{jet}}} \qquad (3)$$

The estimate for the upper limit on the polarization profile factor R can be calculated from this formula assuming that P_0 is conserved during acceleration and it is equal to it's maximum value: $P_{0,max}$ = 80.2% (for Yellow ring). Using P_{jet} =58% from the Table I we can calculate that upper limit for R value is equal 0.15. This number has to be compared to measurements using the p-Carbon polarimeter giving a lower limit: R= 0.11.

The upper limit on P_{coll} can be also calculated using formula (2) and (3):

$$P_{coll} = \frac{2Pjet}{1 + \sqrt{\frac{P_{jet}}{P_0}}}$$

The plot of the upper limit on P_{coll} vs. P_{jet} is presented in Figure 3:

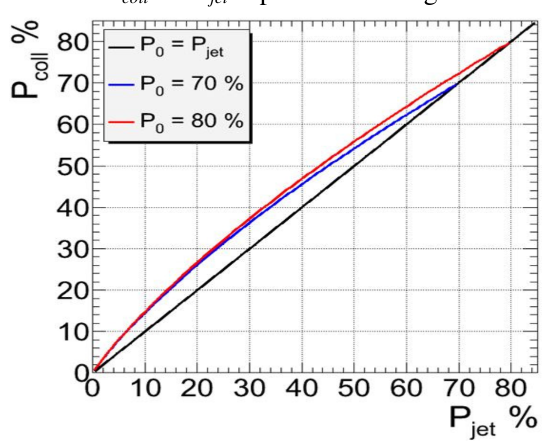

Figure 3: Upper limit on polarization in collision vs. H-jet polarization.

This plot shows that P_{coll} is not very sensitive to the assumption of strict P_0 conservation: at P_{jet} =60% the P_{coll} is changing just 2% when P_0 is changing from 70 to 80%.

For the P_{jet} =57.7% the upper limit on P_{coll} is equal to 62.3% which is to be compared with 60.5% after correction using experimentally measured factor R =0.10 (see Table I). Thus, the upper limit estimate for P_{coll} gives quite a narrow range for actual polarization P_{coll}: 60.5% < P_{coll} < 62.3%. Taking into account that statistical error for the P_{jet} values is ± 3-4% for one eight-hour store and the systematic error is about ± 2%, the systematic error from underestimated polarization profile numbers is not a big factor.

5. Summary

The combination of polarization transport simulation in AGS and RHIC and absolute polarization measurements tools at 200 MeV and RHIC store energies provide complimentary information on polarization losses along the RHIC accelerator chain. Polarization profile measurements by the scanning p-Carbon CNI polarimeters in the AGS and RHIC provide experimental data that depolarization occurs at the edge of the beam and that the polarization of the beam core is preserved during acceleration. While absolute polarization measurements are not available at RHIC injection energy, the measurements of polarization profiles allowed the extrapolation of H-jet and 200 MeV measurements to RHIC injection energy (AGS flattop energy) for better understanding of the polarization losses in AGS and RHIC.

Upper limits on the beam polarization in collisions were estimated using H-jet polarization numbers and the absolute measurements of the source polarization as measured at 200 MeV at injection into Booster. This gives quite a narrow range for polarization in collisions 61-62.3% for presently achieved (for the best running period in Run-2013) average polarization of about 58% at 255 GeV colliding beams energy.

Acknowledgments

The authors are thankful for discussion with the members of the RHIC Spin Collaboration, in particular D.Smirnov and A.Poblaguev contributions in data analysis. This work was supported by BSA, LLC under Contract No. DE-AC02-98CH10886 with the U.S. DOE.

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