Status and future plans of polarized beams at COSY

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Abstract. In this paper we report on the present status and future plans of polarized beams in the COSY synchrotron ring. COSY is a synchrotron ring in the momentum range from 295 to 3700 MeV/c. Polarized deuterons and protons are routinely delivered to experiments over the whole momentum range. No depolarization occurs during the acceleration of deuterons in COSY. For polarized protons many depolarizing resonances are crossed without polarization loss. At imperfection resonances, vertical steerer magnets are used to increase the resonance strength, leading to a complete polarization reversal. At intrinsic resonances a fast tune jump quadrupole is used to quickly cross the resonances without loss of polarization. Typical proton polarizations are close to 0.8 below 2.1 GeV/c and about 0.6 for higher momenta. During recent operation an induced depolarizing resonance was used for accurate determination of the relative momentum spread dp/p of the stored beam yielding an accuracy of better than $10^{-4}$. For spin filter studies of the PAX collaboration a low beta target section was installed in 2009 and was successfully put into operation early 2010. An upgrade of the EDDA polarimeter electronics and data acquisition system is underway to ensure continued availability of the polarimeter, which is essential for the polarized proton operation of COSY. In the near future it is planned to install a Siberian snake solenoid of 4.5 Tm to be able to provide in addition to vertically polarized protons, longitudinal polarization as well. This solenoid will allow the preparation of a longitudinally polarized beam up to a kinetic energy of 500 MeV.

1. Introduction

The COoler SYnchrotron (COSY) of the Forschungszentrum Juelich accelerates and stores polarized and unpolarized protons as well as deuterons up to momenta of 3.7 GeV/c for internal experiments (ANKE, WASA, PAX, EDDA) and for experiments using an extracted beam (TOF) (figure 1) [1]. In the case of protons, a very extensive series of successful measurements with polarized beams and targets was carried out by the EDDA collaboration [2]. The EDDA detector now serves as a powerful polarimeter that can determine the polarization of the beam with high precision. This is essential for the acceleration of polarized protons, as many depolarizing resonances during the acceleration process have to be crossed. Only fast and precise determination of the positions of these resonances allows acting against the depolarization during resonance crossing. COSY continues to supply polarized proton beams to experiments, and is in addition now embarking on an ambitious program of investigations with polarized deuteron beams and polarized hydrogen and deuterium target cells. In section 2 of this paper we report on the present status of polarized proton and deuteron beams at COSY. In section 3 we report near future plans.
2. Status of polarized beams at COSY

2.1. Polarized Ion Source

The polarized proton and deuteron beams are produced in a colliding beam type ion source [3]. It consists of a pulsed polarized hydrogen or deuterium atomic beam source and a cesium ion beam source. The polarization is produced by passing the neutral atoms through a system of sextupole magnets and radio frequency units. The neutral polarized beams are then ionized to H− or D− by colliding with the cesium ion beam. The H− and D−ions transferred via a low energy beam line (4.5 keV/u) to the pre-acceleration in the JULIC cyclotron. The 45 MeV H− or 75 MeV D− beams are then transferred through the injection beam line and strip-injected into COSY. The polarization of the injected beam can be optimized using a low energy polarimeter in the injection beam line to COSY.

2.2. Acceleration of polarized beams in COSY

For an ideal planar circular accelerator with a vertical guide field the particle spin vector precesses around the vertical axis, and the vertical beam polarization is preserved. The number of spin precessions per revolution of the beam in the ring is given by \( v_{sp} = \gamma G \) [4], where \( G = 1.7928 \) and \( G = -0.14298 \) is the anomalous magnetic moment for protons and deuterons, respectively, and \( \gamma \) is the Lorentz factor. During acceleration of a polarized beam depolarizing resonances are encountered if the precession frequency of the spin is equal to the frequency of the spin-perturbing magnetic fields. A strong focusing synchrotron like COSY has two different types of strong depolarizing resonances, namely imperfection resonances caused by magnetic field errors and misalignments of the magnets and intrinsic resonances excited by horizontal fields due to the vertical focusing.

For polarized deuterons no resonances are encountered in the energy range of COSY for regular vertical betatron tunes between \( Q_y = 3.5 \) and 3.66. No polarization loss is expected and observed.

For protons, in the energy range of COSY, six imperfection resonances have to be crossed (table 1). The resonance strength depends on the vertical closed orbit deviation. Vertical correction dipoles or a partial snake can be used to preserve polarization at imperfection resonances by exciting adiabatic...
spin flips. Simulations indicate that an excitation of the vertical orbit by 1 mrad is sufficient to cause a spin flip without depolarization. The vertical correcting dipoles in COSY are designed to increase the vertical orbit deviation by 1 mrad at maximum momentum. Therefore an excitation of complete spin flips is possible by use of vertical steerer magnets, and this method is used in COSY regularly to preserve the polarization at the imperfection resonances by complete spin flips (figures 2,3).

Table 1. The imperfection resonances for protons and their kinetic energy and momentum encountered in the COSY momentum range.

| γG | T_{kin} (MeV) | p (MeV/c) |
|----|-------------|---------|
| 2  | 108.4       | 463.8   |
| 3  | 631.8       | 1258.7  |
| 4  | 1155.1      | 1871.2  |
| 5  | 1678.5      | 2442.6  |
| 6  | 2201.8      | 2996.4  |
| 7  | 2725.1      | 3535.6  |

Table 2. The intrinsic resonances for protons and their kinetic energy and momentum encountered in the COSY momentum range for Q_y = 0.6.

| γG | T_{kin} (MeV) | p (MeV/c) |
|----|-------------|---------|
| 6- Q_y | 317.7       | 832.2   |
| -1+ Q_y | 422.4       | 982.3   |
| 7- Q_y | 841.1       | 1507.8  |
| 0+ Q_y | 945.8       | 1629.5  |
| 8- Q_y | 1364.4      | 2098.1  |
| 1+ Q_y | 1469.1      | 2212.2  |
| 9- Q_y | 1887.8      | 2660.6  |
| 2+ Q_y | 1992.4      | 2771.2  |
| 10- Q_y | 2411.1     | 3209.8  |
| 3+ Q_y | 2515.8      | 3318.7  |

The second types of resonances, the intrinsic resonances, depend on the vertical betatron tune Q_y of the synchrotron. The resonance condition is γ G = k P +/- (Q_y - 2), where k is an integer, P is the superperiodicity of the ring, and Q_y is the vertical betatron tune. For regular operation of COSY the superperiodicity during acceleration is P = 2. The intrinsic resonances encountered in the momentum range of COSY are listed in table 2.

Figure 2. Typical cycle for polarization preservation. The top trace (2) shows the pulses measured at the fast quadrupole, the middle trace (3) shows the vertical correction steerer amplitudes, the lower trace (1) is the beam intensity measured by a beam current transformer (BCT).

Figure 3. Polarization measured with the EDDA polarimeter. Spin flip at the imperfection resonance and the 8- Q_y intrinsic resonance. The Polarization loss at 2200 MeV/c can be attributed to a higher order coupling resonance.

To preserve the polarization at the intrinsic resonances, a fast change of the vertical betatron tune and therefore a fast crossing of the resonance is used. For this purpose, an air core copper coil quadrupole with length of 0.6 m is installed in COSY. It is run in pulsed mode, with currents of up to 3100 A, yielding a max. gradient of 0.45 T/m, rise time of 10 μs, and fall time of 10 to 40 ms. This allows a vertical tune jump of up to Δ Q_y = 0.06 in 10 μs, which allows crossing of all resonances without polarization loss (figures 2,3). The 8- Q_y resonance is rather strong for the superperiodicity of
P = 2, and without the tune jump a complete polarization reversal is achieved, such that for this resonance no action has to be taken. However, because of the strength of the 8- $Q_y$ resonance, the close by coupling resonance is strong as well and leads to significant loss of polarization, especially in the presence of coupling solenoid fields, e.g. the electron cooler solenoids. Below the 8- $Q_y$ resonance polarizations of the polarized proton beam is equal to the polarization of the injected beam, i.e. close to 0.8. Above the 8- $Q_y$ resonance ($p \approx 2.1$ GeV/c), the typical polarization during regular COSY operation is 0.6-0.7.

2.3. Energy calibration with induced depolarizing resonance

For an accurate measurement of the $\eta$ mass in the reaction $dp \rightarrow ^3He\eta$ an accurate determination of the momentum of the stored deuteron beam was of great importance. Under regular operating conditions of the COSY storage ring, the accuracy of the momentum of the stored beam is in the order of $dp/p = 10^{-3}$. To reach a much higher accuracy, the spin resonance method known from energy calibration of electron storage rings has been applied to deuteron beams stored in COSY. This method uses of depolarizing a stored polarized beam by an induced depolarizing resonance [5].

The vertical beam polarization can be perturbed by a horizontal magnetic field in the synchrotron and, if the frequency of the perturbation coincides with the spin-precession frequency, the beam depolarizes. A horizontal rf field from a solenoid can lead to rf -induced depolarizing resonances. The spin-resonance frequency $f_r$ for a planar accelerator is given by $f_r = (k + \gamma G)f_0$, where $f_0$ is the revolution frequency of the beam, $\gamma G$ is the spin tune, and $k$ is an integer.

To determine the deuteron kinematic $\gamma$ factor and thus the momentum, the resonance frequency $f_r$ and the revolution frequency of the beam $f_0$ has to be measured. The revolution frequency can be determined from schottky spectra. The resonance frequency can be determined from depolarization measurements of the beam with fixed frequencies for the rf solenoid. The EDDA polarimeter is used to measure the vector polarization of the beam. The polarimeter is not calibrated for deuteron beams, however, for determination of the depolarization a relative measurement of the polarization is sufficient. The measurement yields an unprecedented accuracy of $dp/p$ of less than $10^{-4}$.

3. Future Plans

3.1. Spin Filtering Studies

The PAX (Polarized Antiproton Experiments) collaboration is working on the long term aim of polarizing an initially unpolarized proton beam by interaction with a polarized internal target in a storage ring (spin filtering) [6]. This spin filtering is today viewed as the only promising method to prepare a polarized antiproton beam. As a first step, the collaboration performs spin filtering experiments with polarized protons in the COSY accelerator to confirm the present understanding of the spin filtering process. In addition the measurements will be used to commission the necessary experimental equipment for possible future experiments at the AD antiproton ring of CERN.

![Figure 4. Low beta function for PAX. The beta function at the PAX interaction point with and without low beta quadrupoles is shown. The rectangles depict the position of the regular COSY quadrupoles (blue) and the additional low beta quadrupoles (red).](image-url)

The operation of the polarized target requires leading the stored beam through a storage cell. Since at injection into COSY the beam is not yet cooled the storage cell should not restrict the acceptance.
To be able to reduce the size of the used storage cell and by this to increase the available target density, a low beta magnet system will be used. The low–β section comprising four additional quadrupole magnets has been installed during 2009. The calculated beta functions in the PAX target region are shown in figure 4. Commissioning took place in January 2010 and COSY was operated with the low beta quadrupoles excited without any noticeable reduction in performance the machine.

3.2. Upgrade of Polarimeter Electronics
The EDDA Polarimeter is an essential tool for measuring and optimization of the polarization of polarized proton beams in COSY. It uses a carbon fiber target, which can be moved into the path of the stored beam. The two protons from pp quasi free elastic scattering are detected in coincidence in scintillation counters. The high rates in the 10 MHz range require fast electronics which is accomplished by using camac logic and scaler units. The data acquisition system is still the original system, and was reliably running for over 20 years. However, in case of any breakdown, it becomes increasingly difficult to get replacement parts today. Therefore it was recently decided to equip the EDDA polarimeter with new readout electronics and data acquisition computers. The new system will be compatible with modern computer components, which ensures easy replacement and continued operation of the polarimeter. This work is well underway and during 2011 the new system will be ready for use.

3.3. Full Snake for longitudinally polarized proton beams
Siberian snakes are used to eliminate depolarizing resonances in circular accelerators. The spin is rotated by 180 degree in the snake, forcing the spin tune to be a half integer, independent of the beam energy [7]. In the presence of a full Siberian snake in one of the COSY straights, the direction of the spin vector has to be longitudinal at the symmetry point of the snake, i.e. 180 degree away on the opposite straight section. At this position an experiment can be placed to use the longitudinally polarized beam. To avoid crossing depolarizing resonances, the snake can be turned on at half-integer spin tune. Then the spin tune is equal to a half integer for any snake strength. This condition is satisfied whenever the kinetic energy $E_{\text{kin}}$ is given by $E_{\text{kin}} = 370 \text{ MeV} + k \times 523 \text{ MeV}$, where $k$ is an integer. In the energy range of COSY only a solenoid field is suitable. A solenoid field for 180 degree spin rotation rotates the transversal phase space by 32.2 degree. This leads to a coupling of the horizontal and vertical phase spaces. The experience at COSY with solenoid magnets at the WASA experiment or the electron cooler has shown that it is not necessary to correct the coupling at higher momenta. Only injection efficiency is reduced, which is avoided by turning on the snake at higher momenta. The additional focusing caused by the solenoid can be compensated by reduction of focusing strength in the surrounding quadrupole triplets.

In a first stage a 4.5 Tm, fast ramping (approx. 30 sec) single solenoid will be installed either at the ANKE target point, providing longitudinal beam polarization at the PAX interaction point, or vice versa. A full snake at 3300 MeV/c requires a solenoid field of 12.4 Tm, three solenoids of the foreseen type could be used to reach this value. At this time the space for such an installation is not available.

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