Polarized Beam Acceleration in the Synchrotron

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Abstract

A polarized beam is required to investigate the spin-dependent experiment. However, the acceleration of polarized beams in circular accelerators is complicated by the numerous depolarizing spin resonances. A polarized beam was accelerated in the intermediate energy strong focusing synchrotron in 70's and 80's. Recently, several plans of polarized beam acceleration up to high energy to realize the polarized beam collider experiment. Depolarizing resonance and curing methods will be mentioned briefly. Further, several plans and performance of the polarized beam acceleration including the electron beam will be presented.

1 Introduction

The large and unexpected spin effects have been pointed out that spin-dependent experiment is one of the frontier research areas in high energy and nuclear physics to investigate the fundamental interaction of elementary particles. For experiments to investigate the pure spin state, a polarized beam is required together with polarized targets. Research and development were carried out of accelerate a polarized proton beam in Saturne II at Saclay[1], KEK-PS[2] and AGS at Brookhaven National Laboratory[3] in 70's and 80's and contributed the spin-dependent experiment with the fixed target.

High energy polarized beam collisions are going to open the unique physics opportunities of studying spin effects and several plans have been proposed and are going on. The acceleration of polarized beams in circular accelerators is complicated by the numerous depolarizing spin resonances, especially up to high energy. Siberian Snake[4] made it possible to accelerate polarized protons up to high energy and several fundamental studies of the Siberian Snake using solenoid magnet have been successfully performed at the IUCF[5]. Full Siberian Snakes are being developed for RHIC to make the acceleration of polarized protons to 250 GeV and a partial Siberian Snake[6] and a rf dipole methods contribute to accelerate the polarized protons to 25GeV at the Brookhaven AGS[7]. A similar scheme is being studied for the 800 GeV HERA proton accelerator[8]. In a few GeV machine, such as the cooler synchrotron COSY, a polarized beam acceleration is going[9] on and a polarized electron beam acceleration at the electron storage ring, ELSA, is also performed[10]. Stored electron beam becomes polarized one by the synchrotron radiation emission, Sokolov and Ternov effect[11], but polarization time in ELSA is estimated as 10-100 minutes[12] and it is too long to use the beam for experiments.

Table 1
Some spin parameters of polarized particle

particle	Gyromagnetic anomaly G	Number of spin rev. per tune	Interval between imp. resonance GeV
p	0.793	few (>2)	0.523
d	-0.143	fewer	11.25
e	1.16×10^{-3}	almost 0	0.440

2 Depolarizing Resonance in a Synchrotron and the Correction Methods

Since there are generally many depolarizing resonances in a strong-focusing synchrotron, a polarized beam cannot be accelerated without using several correction methods to suppress the depolarizing resonances. In a pure vertical magnetic field, the spin of a particle precesses about this vertical field, with a frequency γG(spin tune), where γ is the Lorentz energy factor and $G=g/2-1$ (gyromagnetic anomaly). The strong depolarizing resonances are caused by the horizontal field components of the focusing quadrupole magnets and fringing of the bending magnets. There are basically two types of first order depolarizing resonances. One is an intrinsic resonance which is excited by the periodical focusing structure of the machine. The second type of first-order depolarizing resonance is an imperfection resonance which is due to the magnet misalignment leading to vertical closed orbit distortion (COD). There can also be higher-order resonances and a synchrotron motion for off-momentum particles may cross the resonance many times. All the resonance condition at

$$\gamma G = \mathrm{n}N \pm k \pm m_z\nu_z \pm m_x\nu_x \pm m_s\nu_s \quad (1)$$

where n is an integer, N is a super periodic number, k is a harmonic number of COD, ν_x, ν_x, ν_s are the horizontal and vertical betatron tune and the synchrotron tune, respectively.

Resonance interval and strength are depend on the value of gyromagnetic anomaly. Table 1 shows some spin parameters of polarized particle. Imperfection spin resonances occurs at regular intervals in the kinetic energy. Between these imperfection resonances, there are important intrinsic resonances, higher-order resonances and synchrotron sidebands.

During acceleration of the polarized beam in the synchrotron, many depolarizing resonances must be passed through as the beam energy increases. The polarization P_f after passage through each depolarizing resonance is given by

$$P_f = P_i \left(2 e^{-\pi \varepsilon^2 / 2\alpha} - 1 \right) \quad (2)$$

where *Pi* is the polarization before passing through the resonance, ε is the resonance strength, α is rate of passage[11].

The depolarization is small for $1 \gg \varepsilon^2 / \alpha$, corresponding to a fast crossing or a weak resonance. On the other hand, the spin flips for $1 \ll \varepsilon^2 / \alpha$ with small depolarization. There are several methods to reduce the depolarization if the situation of resonance crossing is a signal isolated spin resonance.

2.1 *Intrinsic resonance*

In order to reduce the depolarization in passing through the weak or intermediate resonance, increasing the rate of passage α is very useful. From eq.(2) it is possible to increase α by rapidly changing the vertical betatron tune ν_z when γG approaches resonance. This method has been quite successfully applied at the AGS[3] and the KEK-PS[2] in 80's. The resonance strength is proportional to the vertical oscillation amplitude and the vertical focusing field. Spin flip by enhancing the resonance is also effective, if the emittance growth can be allowed. This effect was first confirmed at the KEK PS. A novel scheme of overcoming strong intrinsic resonances using a rf dipole magnet was successfully tested at the AGS [7]. Full spin flip can be achieved with a strong artificial spin resonance excited by driving coherent vertical betatron oscillations. This method made complete spin flips at the four strong intrinsic resonances $0 + \nu_z$, $12 + \nu_z$, $36 - \nu_z$ and $36 + \nu_z$ which caused the main origin of depolarization.

Recently, a polarized proton beam was accelerated at COSY to 2.7 GeV/c by a tune jump method together with the changing the optics [9]. Tune jump magnet system consists of two pulsed air core quadrupoles. In ELSA, polarized electron beam was accelerated by the fast tune jump system of two Panofsky type ferrite quadrupoles [10].

2.2 *Imperfection resonance*

In the case of imperfection resonance, the resonance strength can be reduced by correcting the *k*-th harmonic component of the COD. In practice, the orbit correction can be done by using the vertical steering dipole magnets. Increasing the COD or slow passage can make a spin flip. Almost full spin flip can be achieved at COSY and ELSA by a low acceleration rate. A partial Siberian Snake enhances the resonance strength and make a complete spin flip. AGS showed that a 5% partial Siberian Snake is sufficient to accelerate the polarized beam by a spin flip without using the harmonic correction of the COD [12].

2.3 *Higher-order resonances and the synchrotron sideband*

The higher-order resonances can be caused by higher-order nonlinear magnetic fields in the machine. Such resonances can be avoided by increasing the rate of passage α by rapidly changing the betatron tune and by controlling the COD in a similar manner to the first-order resonances. Resonance due to the coupling between the horizontal and vertical betatron oscillations can be avoided by control of the skew quadrupole magnetic component.

Beam is a collection of particles which are bunched by the accelerating rf system and particles oscillate in energy with time around the bunch center at the synchrotron frequency, the particles at the bunch edge can cross resonance a multiple number of times even if the bunch center is accelerated through the resonance with a constant $d\gamma/dt$. Depending on machine parameters, a large depolarization will occur due to the synchrotron oscillation. In order to reduce the amplitude and frequency of the synchrotron oscillation, the accelerating rf voltage must be decreased. However, there are limitations to this method because the low-rf voltage makes the momentum acceptance small.

2.4 *Siberian Snake*

There are numerous depolarizing resonances to higher energy, then the above conventional methods are complicated. Further, several and many resonances would be overlapped in the beam bunch of 0.3%-0.5% momentum spread. Then the Siberian Snake is consideration to be moderate and easy method. Derbenev and Kondratenko proposed a unique and noble method[4] to overcome all of these spin resonances. It was called Siberian Snake which is local spin rotator that precess the particle spin by 180° about a horizontal axis. The spin tune may become 1/2 by the Siberian Snake and can avoid all of the spin resonance conditions including overlapping resonances. Since the spin tune is independent of the energy of the particle as shown in eq.(3). This scheme would greatly help the polarized beam acceleration through spin resonances in the high energy accelerator.

The spin tune (ν_{sp}) is indicated as,

$$\cos(\pi \nu_{sp}) = \cos(\pi \gamma G) \cos(\delta/2) \qquad (3)$$

then, $\delta = 180^\circ \rightarrow \nu_{sp} = 1/2$: full snake
$\delta = 0^\circ \rightarrow \nu_{sp} = \gamma G$: no snake
$\delta \ll 180^\circ$: partial snake

For a spin rotation of 180^{O} by solenoid ,

$$B.\, l = 3.52\, \beta\gamma \ \ (\mathrm{T.m}). \qquad (4)$$

This equation suggests that the solenoid should have to be ramped to acceleration energy exactly. Solenoid fields strength for $\theta = 180^{\mathrm{O}}$ to accelerate protons are follows,

100MeV	1.67 (T.m)	
1GeV	6.37 (T.m)	
5GeV	22.0 (T.m)	(c.f. 2.742 x 8 = 21.9)
10GeV	40.9 (T.m)	

On the other hand, magnets array of spin rotator is grate advantage in the high energy region since magnetic rigidity is independent on energy. Many schemes are proposed and under reserch[13].

Fundamental experiments using a solenoid snake has been carried out at the IUCF Cooler Ring[5]. These successful experiment results at the IUCF are very encouraging for polarized beam project at RHIC and HERA.

4 Status of the Polarized Beam Acceleration

After terminated of polarized beam project at Satune II and KEK-PS, several facilities have continuing the polarized project for the spin experiment of nuclear and particle physics[13]. Recently, COSY and ELSA accelerated polarized protons and electrons using a conventional method, respectively, as mentioned above.

The studies of polarized proton acceleration using the solenoid Siberian Snake has been continuing at the IUCF Cooler Ring. It was shown that the Siberian Snake concept were completed and proofed [5] including that an artificial spin resonance can be used to flip the spin of a store polarized beam even in the presence of a full Siberian Snake.

Polarized protons from the AGS will be injected into the two RHIC rings to aim the polarized proton collisions up to 500GeV center of mass energy with collaboration between BNL-RIKEN[14]. Siberian snakes (two for each ring) and the spin rotators (four for each collider experiment) for RHIC consists of four 2.4 m long, 4T helical superconducting dipole magnets of 360 degree helical twist[15]. Helical magnets reduce orbit excursions without the extend of the snake or spin rotator.

For HERA polarized proton project, which could be collided with HERA's polarized electron beam by synchrotron radiation emission and scattered by an internal polarized proton jet target, needs two full Siberian Snakes in PETRA and at least four full Siberian Snakes in HERA to 920 GeV. However, these four snakes might be inadequate to overcome HERA's strong depolarizing resonances, then six or eight snakes, which suggest the evacuation of more space in the ring, are strongly investigated.

Deuterons consist of a loosely bound proton and neutron system. The deuteron mass is almost twice that of the proton, and the anomalous magnetic moment, (G) is -0.143 as shown in Table 1. Therefore, polarized deuterons are more easily accelerated than protons. In the past, polarized deuteron was accelerated at Dubna and ZGS. Feasibility study of the accelerating polarized deuteron in the AGS and RHIC was performed[16]. KEK-PS performed the test of polarized deuteron acceleration in 1996[17] and after that polarized project at the KEK-PS was terminated.

Spin physics experiments at the JHF(now Joint Project between KEK and JAERI) 50GeV PS are requested[18]. Design of the polarized beam acceleration is not considered in detail, but Siberian Snake should be adopted in order to overcome the numerous strong resonances, if the possibility of laser polarization[19] would not be realized. Helical magnets have some distinctive advantages, then the results of RHIC and HERA spin projects are worthy of notice. Finally, we have a good text book to study the spin dynamics in the synchrotron[20], and the University of Michigan High Energy Spin Physics Center open a home page of Spin Physics[21].

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