REVIEW OF POLARIZED HADRON BEAMS

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Abstract : A review of facilities for acceleration of polarized hadron beams is given. Recent relevant results are presented with an emphasis on the depolarizing resonance crossing techniques used in synchrotrons.

1. Introduction

1.2. Historical summary

The acceleration of polarized hadron beams to high energy has been contemplated for many years. By 1960, sufficient progress had been made in the development of polarized sources for considering this possibility and some theoretical works were devoted to investigating the spin motion in a high energy synchrotron. The behavior of polarized protons in the 3 GeV SATURNE synchrotron at Saclay was studied by M. Froissart and R. Stora in 1959[1]. They showed that magnetic field inhomogeneities could excite depolarizing resonances during the acceleration cycle and they calculated the effect of an isolated resonance crossing. Not long after, the problem was also examined by D. Cohen[2] for the ZGS at Argonne and by E.D. Courant[3] for the Brookhaven AGS.

Serious depolarizing resonances were found but some procedures were suggested for avoiding or minimizing their effects, so that there were still some hope for overcoming large depolarization.

During the following years, development of high current polarized sources and further theoretical studies which confirmed the earlier works finally led to the decision to accelerate polarized protons in the ZGS.

The first beam was accelerated in July 1973[4]. During the four next years, there were numerous improvements in intensity, reliability and understanding and by 1977 it was possible to accelerate 4 10^{10} polarized protons per pulse up to 12 GeV with negligible loss of polarization.

The success of the ZGS and the growing interest for higher energies stimulated new detailed investigations of resonant depolarization in strong focusing synchrotrons. In 1975, calculations related to the SATURNE 2 synchrotron at Saclay predicted that complete spin flip should occur during the crossing of most of the resonances encountered[5]. Two years after, a workshop organized at Ann Arbor concluded that acceleration of protons to 25 GeV looked possible in machines like the CERN PS or the AGS.

It followed that after the shutdown of the ZGS in 1979, polarized protons acceleration projects started at Saclay, Brookhaven and KEK. The slow adiabatic resonance crossing was successfully applied at SATURNE 2 in 1981-82 to reach 2.4 GeV with 80 % polarization[6]. In summer 1984, the AGS accelerated a beam to 16.5 GeV with 40 % polarization[7] and finally, the KEK PS (booster + main ring) accelerated protons to 3.5 GeV in 1986[8].

1.2. Outline of review

If high energy requires synchrotrons, that is circular machines, lower energies are achievable with accelerators like Van de Graaffs, linacs and cyclotrons. In this domain, numerous machines have been equipped with polarized sources for many years. There is generally no problem associated with acceleration except for TRIUMF where a small effect has been measured and the Manitoba cyclotron where complete depolarization of H^- ions has been observed [9].

Within the limited scope of this survey, it is impossible to describe all the existing facilities in this energy region. I shall thus limit this review to medium or high energy facilities which have been presented at the Eighth International Symposium on High Energy Spin Physics.

I shall first review briefly medium energy beams accelerated in linacs or cyclotrons, that is without noticeable depolarization problem, at PSI, TRIUMF and LANL. Beams accelerated in synchrotrons at LNS, BNL, KEK will be then examined in more details with emphasis on techniques used to reduce the effects of depolarizing resonances. Finally, the particular case of the FNAL high energy beam will be presented.

In conclusion, perspectives for future very high energy beams will be briefly outlined and recent experimental results from the first experimental test of the Siberian Snake concept at IUCF will be discussed.

2. Operating polarized beams

2.1. Medium energy beams

In the area of medium energy, the three meson factories at LAMPF, PSI and TRIUMF have developed polarized beams facilities.

At LANL, polarized beams activities are a substantial part of the nuclear physics experimental program. Until 1988, the LAMPF linac was equipped with a Lamb-shift polarized H^- source and was able to deliver $\sim$ 20 nA proton beam at 800 MeV (9 % duty cycle) or $\sim$ 7 nA at lower energies down to 212 MeV (3 % duty cycle) with 70-80 % polarization[10]. In typical operation, most of the beam was delivered to a liquid deuterium neutron production target with smaller currents delivered to two other beamlines.

In 1988, the Lamb-shift source has been turned off for the last time to be replaced by an optically pumped polarized ion source (OPPIS). This new source was operated in september 1989 for a nuclear physics experiment with 8 μA peak current and 45 % polarization passing largely in P^2I (the common figure of merit for polarized beams) the performances of the Lamb-shift source[11]. The present level of performances is 50 μA with 50 % polarization and higher values are expected for the next months[12].

At PSI, the polarized source is of the atomic beam type, it produces protons and deuterons which can be accelerated to low or medium energy. At low energy (72 MeV protons), polarized beams are accelerated in the injector cyclotron then directed to one of the three low energy experimental areas with adjustable polarization orientation. One area is dedicated to production of monoenergetic polarized neutrons with energies between 30 and 70 MeV by transverse proton-neutron spin transfer on a liquid deuterium target. Fluxes of up to 5 10^5 n/s.cm^2 with 35 % polarization are obtained. Protons can also be injected at 72 MeV into the ring cyclotron and accelerated to medium energy (590 MeV). They are used to produce polarized neutron fluxes of about 50 10^5 n/s.cm^2 with 40 % polarization and energies between 200 and 580 MeV by longitudinal polarization transfer on a carbon target.

Two years ago, the proton beam intensities were 3 μA to 6 μA at 72 MeV and reached 5 μA at 590 MeV with 90 % polarization [13]. Recently, these performances have been significantly increased by the installation of an ECR ionizer in the source. Mean intensities now reach 12 μA at 72 MeV and $\sim$ 10 μA at 590 MeV. The polarization has been slightly reduced ($\lesssim$ 80%) but it is planned to improve it in a near future[14].

Experiments with polarized beams are an important part of the research program, especially at low energy, since more than 50 % of the operation time of the 72 MeV cyclotron was dedicated to the acceleration of polarized protons and deuterons in the last years [13].

Like other meson factories, TRIUMF has a strong program in spin physics since 39 % of the running time was devoted to accelerating polarized beams in 1988[15].

In past years, TRIUMF was using a Lamb-shift polarized H^- source to provide about 1 μA of 75 % polarized protons between 200 and 500 MeV. With such incident beams, secondary polarized neutron beams could be produced from a liquid deuterium target with fluxes up to 10^5 n/s.cm^2 [16].

Recently, an optically pumped polarized H^- source has been installed and connected by a 45 m beam line to the cyclotron [17]. H^- currents of up to 8 μA have been obtained and after acceleration in the cyclotron, a proton polarization of 50 % has been achieved.

Today, acceleration of polarized protons is considered in the accelerators of the proposed Kaon Factory. From recent studies [18], the total depolarization is expected to be about 30 % for a 10 μA proton beam with 80 % initial polarization.

2.2. Medium and high energy beams accelerated in synchrotrons

As pointed out in the introduction, maintaining the polarization of a beam in a high energy synchrotron is a difficult task because several depolarizing resonances have to be crossed during the acceleration cycle. These resonances occur when the energy dependent spin tune $\nu = \gamma G$ (where G is the anomalous magnetic moment coefficient and γ is the relativistic energy factor) is equal to one of the frequencies contained in the spectrum of the horizontal fields seen by particles.

There are basically two important types of resonances :

– imperfection resonances induced by field errors generating a vertical closed orbit. They are encountered whenever $\nu = n$ (n being a positive or negative integer). Most harmful harmonics are those for which $n = KM \pm p$ where M is the number of periods, K and p are integers with p close to ν_z (vertical betatron tune)

– intrinsic resonances induced by main quadrupoles focusing field. The resonance conditions are given by $\nu = n \pm \nu_z$ with $n = KM$. If gradient errors are included some harmonics are enhanced, they are given by $n = KM \pm p$ with p close to 2 ν_z.

It is interesting to notice that for protons, imperfection resonances are separated by $\Delta E = m_0c^2/G = 523$ MeV, it means that in a high energy machine like the AGS, about 50 resonances of this type have to be crossed during acceleration.

Evidently, other sources of spin perturbations may exist (fringing fields, skew or normal multipoles, synchrotron oscillation...). It follows that the general resonance conditions are in fact given by :

$$\nu = n + n_x\nu_x + n_z\nu_z + n_s\nu_s$$

where ν_x, ν_z are the horizontal and vertical betatron tunes, ν_s is the synchrotron oscillation tune and n, n_x, n_z, n_s are positive or negative integers.

Traditional methods of correcting these resonances are based on the analysis of the Froissart and Stora formula which gives the final polarization P_f after the crossing of an isolated resonance with constant acceleration rate α.

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

P_i is the initial polarization, ε is the resonance strength, $\alpha = G\dot{\gamma}$ for imperfection resonances or $G\dot{\gamma} \pm \dot{\nu}_z$ for intrinsic resonances ($\cdot \equiv \frac{d}{d\theta}$ where θ is the azimuthal angle).

The aim of the correction is to increase or to decrease the ratio ε^2/α in order to obtain $P_f = \pm P_i$ after passage through the resonance.

In the case of strong isolated resonances (ε large) natural spin flip may occur and $P_f \approx -P_i$ without any correction.

As will be seen later, these methods have been successfully tested and applied at BNL, at KEK and at LNS.

2.2.1. AGS polarized beam

At BNL, first polarized proton beams (10^{10} ppp) were accelerated in the AGS to 16.5 GeV/c with 40 % polarization in 1984. During the second run in 1986, 46 % polarization was achieved at 22 GeV/c with an intensity of 2.10^{10} ppp. Finally, a third run took place in 1988 and about 2.10^{10} ppp have been extracted at 18.5 GeV/c with polarization between 40 % and 50 % .

General outlook

The system which allowed to achieve these performances has been presented in numerous reports[19, 20] and is described in details in a paper recently published in Physical Review D[21]. Main features are the following.

A cold atomic beam source produces short pulses (300 to 500 μs) of H^- ions with $\sim$ 30 μA current and about 75 % polarization. This beam is extracted from the source at 20 keV and is accelerated to 760 keV by a RFQ with a transmission efficiency better than 80 %. It is then injected into the AGS Linac and accelerated to 200 MeV. Finally H^- ions are injected into the AGS and converted into protons using a carbon stripping foil.

Three polarimeters are used to monitor the beam polarization. The 200 MeV polarimeter placed at the linac exit measures the beam polarization before injection into the AGS, the internal polarimeter located inside the synchrotron is used for resonance crossing studies and the high energy polarimeter gives the final polarization of the extracted beam.

Depolarizing resonances correcting techniques

During acceleration to 22 GeV/c, 7 intrinsic resonances and 39 imperfection resonances have to be crossed and therefore corrected. In order to minimize polarization losses, two different procedures are used :

– intrinsic resonances are "jumped" that is crossed in less than one turn ($\alpha = \dot{\gamma}G \pm \dot{\nu}_z$ very large) by using 10 fast pulsed quadrupoles which generate a fast vertical tune shift ($\Delta\nu_z \sim 0.25$ in 2 μs) just before crossing the resonance

– imperfection resonances are corrected by using 95 existing dipoles in the ring to cancel the appropriate harmonic n of the perturbing field at each $\gamma G = n$ resonance (ε is then close to zero).

The horizontal correction field has the form :

$$B_n(\theta) = A_n\ \sin(n\theta) + B_n\ \cos(n\theta)$$

where A_n and B_n are determined experimentally by maximizing the polarization. Fast pulsed power supplies allow 50 corrections per AGS cycle.

Present performances and future developments

Figure 1 taken from ref. 21 summarizes the performances which have been achieved at the AGS. About 10 % of the polarization is lost between injection and 13 GeV/c where P = 65 % . The main loss occurs near 14 GeV/c, it is probably caused by interferences between two adjacent resonances ($\gamma G = 36 - \nu_z$ and $\gamma G = 27$). Beyond 14 GeV/c the polarization is almost constant and is equal to 46 % at 22 GeV/c for 2.10^{10} polarized protons per cycle.

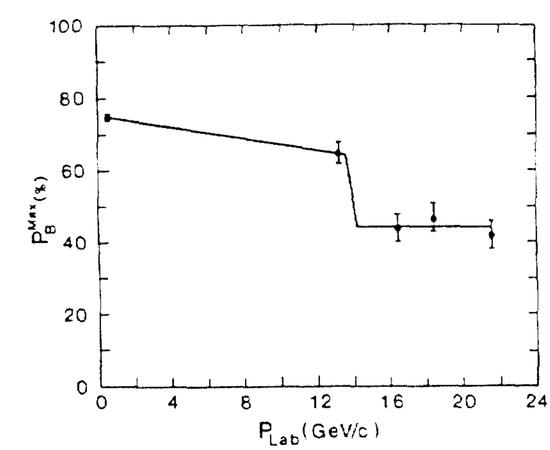

Fig.1 : The maximum AGS beam polarization vs beam momentum

In the near future, major improvements of the beam intensity are expected. First, the new 1.5 GeV booster/accumulator will be able to store up to 20 linac pulses before injecting them into the AGS. Second, ongoing source developments should lead to a ten times enhanced current. The result is that the intensity of the beams accelerated in the AGS would reach about 4.10^{12} ppp.

Another important improvement is actually under consideration, it concerns the possibility of installing a partial Siberian Snake in the AGS in order to eliminate imperfection resonances and therefore to considerably decrease the tune up time.

2.2.2. The KEK PS polarized beam

At KEK, first acceleration test of polarized proton beam in the 500 MeV booster started in 1983. The polarization of the extracted beam was then about 15 % .

In 1986, 40 % polarization has been obtained at 3.5 GeV after the successful acceleration of the beam in the 2 rings of the KEK PS (booster + main ring). Since then, up to 10^{10} polarized protons per pulse have been accelerated to 5 GeV with 25 % polarization and preliminary tests at 7 GeV have been carried out[22].

Polarized beam production and acceleration system

The polarized beam is produced from an optically pumped H^- ion source giving 60 μs pulses with 60 μA current and 65 % polarization. H^- ions are then accelerated by a 750 keV pre-injector and a 40 MeV linac before being injected into the booster and converted into protons. At 500 MeV, polarized protons are extracted from the booster and injected into the 12 GeV main ring.

Four polarimeters are used to measure the beam polarization at different energies. The 20 MeV polarimeter is located between the two linac tanks to measure the initial polarization, the injection polarimeter and the main ring polarimeter are inside the 12 GeV machine to monitor the depolarizing resonances corrections in the 2 rings, the external polarimeter measures the polarization of the extracted beam.

Depolarizing resonances and correction methods

In the booster, two pulsed dipoles and two pulsed quadrupoles have been installed to correct or to cross rapidly the four expected resonances : $\gamma G = 2$, ν_z, ν_x and $5 - \nu_z$. In spite of these equipments, only 75 % of the initial polarization was achieved at 500 MeV. Detailed experimental investigations have shown that the loss was depending on synchrotron oscillation amplitude and that it was probably due to multiple crossings of the $\gamma G = \nu_z$ resonance. By using additional sextupoles to modify the natural chromaticity the 25 % polarization loss could be reduced to about 18 %[23].

In the main ring, there are 4 intrinsic resonances and 9 imperfection resonances between 500 MeV and 5 GeV. The adiabatic spin flip method is used to cross the 2 strongest intrinsic resonances, the two others are "jumped" using four pulsed quadrupoles which have rise times of 40 μs to 200 μs. Only 4 of the 9 imperfection resonances have to be corrected by means of the 28 correction dipoles located near the defocusing quadrupoles.

The polarization at various energies obtained so far are the following : 45 % to 55 % at 500 MeV, 34 to 40 % at 3.5 GeV and about 25 % at 5 GeV. As a preliminary result, 8 % polarization has been obtained at 7.6 GeV.

2.2.3. The SATURNE polarized beams

At LNS, polarized protons were accelerated in SATURNE, a 3 GeV strong focusing synchrotron, as early as 1981. By using the spin flip method to cross the strongest resonances and by correcting the others, it was rapidly possible to obtain 10^9 polarized protons per cycle from 500 MeV to 2.4 GeV with 80 to 90 % polarization[24].

Successive improvements of the polarized source and of the transfer line between the linac and SATURNE led to a continuous increase of the intensity which reached 2.10^{10} ppp in 1986. In 1987, a drastic upgrade occurred with the commissioning of the injector MIMAS. With this new booster/accumulator ring, a record intensity of 2.10^{11} polarized protons or deuterons per pulse has been obtained[25]. Unfortunately, new depolarization problems arose, partly in MIMAS which is a low energy strong focusing synchrotron and mainly in SATURNE which had to be modified for the fast injection of the MIMAS beam.

Now, the MIMAS-SATURNE complex is completely operational and provides routinely proton and deuterons beams with both large intensity and large polarization (90 % to 75 %) between 100 MeV and 3 GeV (protons) or 2.3 GeV (deuterons).

The polarized ion source

The polarized source (Hyperion) is of the atomic beam type. It is placed on a 400 KV platform and provides pulses of width about 1 to 2 ms with a peak current of 500 μA which are extracted at 17 keV from the ionizer[26].

After the 400 KV accelerating gap, the output current is about 320 μA and the polarization is typically 90 % . The transverse normalized emittances are 10^{-5} m.rd and the internal energy spread is 3.2 keV.

The beam is then transported to MIMAS by a 40 m beam line but only a small part of the source intensity is injected into MIMAS because of the multiturn injection process which limits the MIMAS acceptance at injection to about $0.6.10^{-6}$ m.rd (normalized value) in the horizontal plane.

Depolarization problems in MIMAS

Polarized protons are injected into MIMAS at 400 keV (γ = 1.0004) and are extracted at 46 MeV (γ = 1.05) [27]. γG being almost constant during the acceleration cycle, the periodicity of the ring and the working point in the betatron tunes diagram have been carefully chosen in order to avoid the proximity of intrinsic resonances $\gamma G = KM \pm \nu_z$. Nevertheless, even with a corrected chromaticity, the vertical tune spread is about $\Delta\nu_z \sim 0.1$, because of space charge, after trapping of a beam of 2.10^{11} protons with 310.10^{-6} m.rd horizontal emittance, 900.10^{-6} m.rd vertical emittance and 8 % momentum spread.

Some weak defect resonances are thus inevitably crossed because of the synchrotron oscillation.

It has been demonstrated that the $\gamma G = 4 - \nu_z$ resonance (enhanced by the proximity of the quadrupolar $2\nu_z = 4$ resonance) was the cause of a polarization loss which depended on the ν_z spread (that is on the intensity) and, of course, on the vertical emittance.

An attempt to correct this line has been made using two correction quadrupoles, but it appeared that the polarization loss could not be completely suppressed. In spite of this unsatisfying result, the problem has been finally overcome by simply changing the vertical betatron tune value.

Depolarizing resonances in SATURNE

In SATURNE, polarized protons have to cross 6 imperfection resonances : $\gamma G = 2$ to 7 and 2 strong intrinsic resonances : $\gamma G = \nu_z$, $\gamma G = 8 - \nu_z$ ($M = 4$ periods and $\nu_z \sim 3.6$). In addition to these main lines, there are some "weak" resonances induced by gradient errors ($\gamma G = 7 - \nu_z$, $\nu_z + 1$, etc...) which produce up to 20 % polarization loss.

Basically, 3 techniques are used to maintain the polarization all along the acceleration cycle :

– imperfection resonances are corrected or widened (to obtain complete spin flip), if necessary, by using some of the 24 correction dipoles in the ring
– intrinsic resonances are crossed with almost 100 % spin flip by modifying artificially the crossing speed $\alpha = \dot{\gamma}G \pm \dot{\nu}_z$ by means of the main quadrupoles power supply
– weak resonances are corrected by using existing correction quadrupoles initially installed in the ring to compensate for quadrupolar stopbands.

For deuterons, resonances could be avoided by properly choosing the periodicity and the working point.

All the mentioned resonances have been studied in past years. Nevertheless, it has been necessary to reconsider all the corrections after the modifications made to SATURNE for the fast injection of the MIMAS beam.

Present performances and developments in progress

As said before, up to 2.10^{11} polarized protons and deuterons have been accelerated in MIMAS and SATURNE. As shown in Fig. 2, the polarization of the proton beam extracted from SATURNE is ~ 90 % up to 700 MeV and ~ 75 % at 2.7 GeV (2 external polarimeters are available for these measurements).

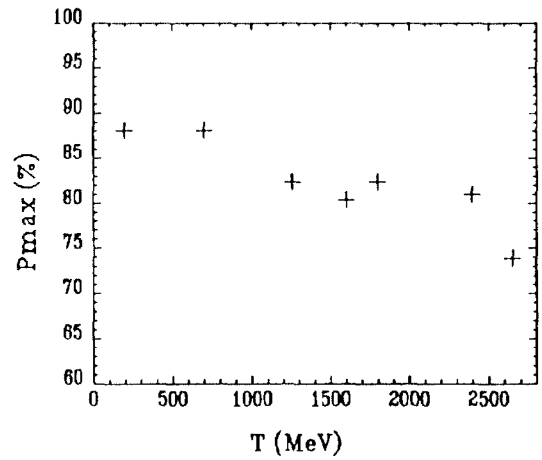

Fig.2 : The maximum proton beam polarization vs beam energy.

Presently, developments of the Hyperion source are in progress to raise the intensity and the brilliance of the extracted beam. A peak current of 700 μA has been recently extracted from an upgraded ANAC *ionizer without deterioration of the emittances. In addition,* a new polarized $^6Li^{3+}$ ion source has been installed and connected to MIMAS and a first Physics experiment with polarized $^6Li^{3+}$ ions is planned for the coming weeks.

2.3. The FNAL High Energy Polarized Beam Facility

A high energy polarized beam facility has been built at Fermilab. It provides the highest energy polarized beam in the world (185 GeV) and the only available polarized antiproton beam[28].

The polarized protons and antiprotons are produced from the parity violating decays of Λ and $\bar{\Lambda}$ hyperons which are created when the 800 GeV unpolarized proton beam strikes a beryllium production target. The beam particle polarization is determined from the correlation between the position at the virtual source and the proton (antiproton) momentum direction. This allow the selection of a beam of particles with definite polarization in a narrow band of momentum.

After the production target a 350 m beam line collects and transports a clean sample of tagged polarized protons (antiprotons) with definite energy (185 GeV). At the end of this line, a set of 12 magnets (spin rotator) is used to rotate or reverse the polarization direction at the final target[29].

With 10^{12} incident protons (20 s-spill), the total number of polarized protons at the final target is 9.10^6. The total number of *tagged protons is 6.10^6 and about half of them have a polarization* greater than 35 % and a 45 % average polarization. Polarized antiprotons intensity is roughly 18 times lower than that of polarized protons.

Several modifications have been already planned to improve these performances. The use of superconducting magnet is also under consideration in order to increase the present energy of 185 GeV up to 600 GeV.

3. Perspectives for future accelerators

Nowadays, acceleration of polarized protons is contemplated in existing or future high and very high energy machines like KAON, RHIC, the Tevatron, UNK and the SSC.

Conventional techniques are obviously inappropriate for maintaining the polarization in most of these machines both because the number of resonances increases dramatically ($\gamma G \sim 36000$ at 20 TeV in the SSC) and because the resonances become stronger and stronger as the energy goes up ($| \varepsilon | \propto \gamma$ for imperfection resonances and $| \varepsilon | \propto \sqrt{\gamma/\beta}$ for intrinsic resonances).

A new method allowing to overcome all resonances rather than correct or jump them one by one is thus desirable. Fortunately, such a solution existed theoretically in the form of the famous "Siberian Snake" which had been proposed in 1974 by Y. Derbenev and A. Kondratenko[30].

The basic principle of the Siberian Snake is to rotate the spin by 180° about an axis lying in the horizontal plane on each turn in the ring. With these successive phase shifts, small kicks due to depolarizing fields are no longer cumulative over many turns but, on the contrary, cancel exactly over two consecutive turns. In other words, the Snake gives rise to a constant spin tune ($\nu = 1/2$) and thus avoids the resonance crossing.

In order to test these theoretical properties, an accelerator physics experiment was done last year at the Indiana University Cooler Ring with polarized protons. One imperfection resonance $\gamma G = 2$ at 108 MeV and one intrinsic resonance $\gamma G = -3 + \nu_z$ at 177 MeV have been successfully overcome by using a superconducting solenoid to rotate the spin about the longitudinal axis[31]. The validity of the Siberian Snake principle has been therefore demonstrated and there is thus now no reason to think that acceleration of polarized protons to multi-TeV energies is an insurmountable problem.

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