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STORING AND COOLING OF POLARIZED IONS*

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ABSTRACT

Storing and synchrotron acceleration of medium energy ions for nuclear physics is reviewed. Apart from the standard vertical spin orientation, other orientations at the target location become possible by using a Siberian snake. In particular, longitudinal vector polarization and second rank tensor polarization with arbitrary orientation of the symmetry axis can be produced. It is shown that electron cooling does not cause depolarization of the circulating ions.

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INTRODUCTION

Due to the strong spin dependence found in medium energy proton-proton and proton-nucleus collisions, there is a growing interest for polarized beams in this energy domain. Storing and electron cooling of polarized ions have been proposed so far for the cooling ring projects at IUCF¹, Uppsala (Celsius)² and Jülich (COSY)³. This paper reviews briefly the problem to accelerate polarized ions and the solutions found in high energy machines. On this basis, the special requirements for nuclear physics experiments in a cooler ring are discussed.

As for unpolarized circulating ions, the goal for polarized stored particles like protons and deuterons will be to perform high resolution studies with thin internal targets. In addition, polarized circulating ions may open up the possibilities to produce intense beams of polarized secondary particles like neutrons with excellent energy resolution. In all cases, permanent cooling is necessary.

What are the requirements imposed by the experiment? We assume that a polarized beam is injected into the ring and that the polarization is high and all the necessary polarization states can be produced by the source. For the various observables, different spin orientations at the target are necessary:

- (i) Vertical spin. This is the standard orientation in a storage ring. It is used for measurement of iT_{11} (vector analyzing power) and C_{nn} (spin correlation coefficient with transverse spin).
- (ii) Longitudinal spin. This orientation is required for the measurement of T_{20} (tensor analyzing power for $s > 1$, e.g. deuterons) and C_{11} (spin correlation coefficient with longitudinal spin).

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(iii) Other orientations. An orientation of 45° to the beam in the scattering plane is needed to measure T_{21} (tensor analyzing power for $s > 1$).

In the following, we will try to answer the question to which extent we can hope that the above requirement can be met.

SPIN RESONANCES IN CIRCULAR MACHINES

We restrict ourselves to heavy particles like protons, where no self-polarizing and self-cooling mechanisms, as in the case of electrons, are present at the energies under discussion. A number of excellent papers on the acceleration of polarized ions in synchrotrons exist^{4,5,6,7,8} and will be referred to in the following.

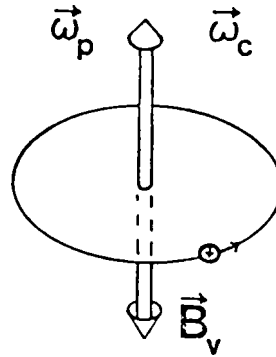


Fig. 1: Orientation of the precession frequency ω_p for a positive ion with $G > 0$.

Let us start to consider the effect of the vertical guiding field on the spin motion. We write (see Figure 1):

$$\frac{d\vec{S}}{dt} = \frac{e}{\gamma mc} [1 + \gamma G] \vec{S} \times \vec{B} = \vec{\omega}_p \times \vec{S}$$

$$\vec{\omega}_p = - \frac{e}{\gamma mc} [1 + \gamma G] \vec{B} = \omega_c [1 + \gamma G] \hat{y} \quad (1)$$

with
$$\omega_c = \frac{eB_v}{\gamma mc}$$

Here \vec{S} is the spin vector in the rest frame, \vec{B} is the magnetic field strength in the laboratory frame and $G = (g-2)/2$ the gyromagnetic anomaly (see Table 1). For a vertical orientation of \vec{S} the spin is stationary; otherwise, the horizontal component precesses with angular frequency ω_p , which can be expressed as a multiple of the revolution frequency ω_c . For example, protons of 108 MeV ($\gamma G = 2$) perform 3 spin rotations per turn, protons of 631 MeV ($\gamma G = 3$) 4 rotations, etc.

Ion	Gyromagnetic anomaly G	Number of spin rev. per turn ($\omega_p - \omega_c$)	Lowest imperfection res.	
			n	T/GeV
p	.793	few (> 2)	2 3	0.108 0.631
d	-0.143	fewer	-1	11.25
paramagnetic ion $\mu \approx \mu_{Bohr}$ $m \approx m_p$	$\approx 10^3$	$> 10^3$ (\rightarrow depol.)	-	-
e, ν	1.16×10^{-3}	≈ 0	1	0.440

Table 1: Some parameters relevant for storage of polarized ions

In a real machine, there are radial and longitudinal components of the magnetic field from the focussing and stray fields, and from magnet imperfections. We refer the generalized precession frequency ($\vec{\omega}_p$) relative to the frame rotating with ω_c :

$$(\vec{\omega})_{rot} = - \frac{eB_v}{\gamma mc} \left[(1+G) \frac{B_{||}}{B_v} + \gamma G \frac{\vec{B}_r}{B_v} + \gamma G \hat{y} \right] \quad (2)$$

The main sources of these fast-varying fields are field errors leading to vertical closed orbit distortions ("wave number" n =integer) or vertical betatron oscillations ("wave number" of the corresponding field distortion: $kP \pm Q_v$; P = machine periodicity, Q_v = vertical betatron tune).

Under most conditions, the spin precession caused by horizontal field components averages to zero and the vertical spin direction would still be quasi-stationary. Only if the wave number γG of the vertical precession comes close to one of the horizontal wave numbers, these small horizontal precession angles add up coherently and a sizeable spin precession arises⁴. The conditions for these so-called depolarizing resonances are the following (for more general conditions, see ref.7):

$$(i) \text{ imperfection resonances: } \gamma G = n \quad (3a)$$

$$(ii) \text{ intrinsic resonances : } \gamma G = kP \pm Q_v \quad (3b)$$

Imperfection resonances are fixed in energy, whereas the position of intrinsic resonances depends on the betatron tune of the machine. The location of the lowest imperfection resonances for some typical ion species are given in Table 1.

STORAGE AND ACCELERATION

If a polarized beam with vertical spin is injected at a certain energy γ_0 sufficiently distant from a resonance and stored, one would not expect any depolarization.

To my knowledge, only one experimental study has been done so far on this problem. At the ZGS, using an extended 21 s flat-top at 3.25 GeV/c, an upper limit for the depolarization rate of 0.025% per second was found⁹. This value corresponds to a 1/e polarization life time of more than one hour, which is much more than the cycling times envisaged for proton storage rings^{3, 10}. Therefore, even if one admits the influence of other neighbouring resonances, the depolarization of the stored beam due to spin resonances should be negligible, at least under the condition of the ZGS experiment. But depolarization rates in a proton storage ring with strong cooling by a cooler and simultaneous strong heating by an internal target have not been studied yet. It was pointed out in ref. 11 that depolarization away from resonances requires the simultaneous presence of scattering and damping processes. This led to the conjecture¹² that polarized proton beams simultaneously heated and cooled would be subject to depolarization, by a process similar to that of quantum fluctuations and radiation damping in electron storage rings. This would suggest a polarization lifetime of the order of the beam lifetime without cooling, but requires a more specific calculation for this situation.

If the particle energy in the cooler synchrotron is varied, the left hand side of eq.(3) changes and the resonance condition may be fulfilled. In their pioneering paper⁴, Froissart and Stora obtained the following formula for the polarization P_f after having crossed an isolated resonance:

$$P_f/P_i = 2 \exp[-\pi \epsilon^2/2\alpha] - 1 \quad (4)$$

with

P_i = initial polarization
 ϵ = strength of the resonance
 α = parameter which describes the speed of the resonance crossing (e.g. $\alpha = G\gamma/\omega_c$ for an intrinsic resonance).

The relevant parameter is $\epsilon^2/2\alpha$. The two limiting cases are:

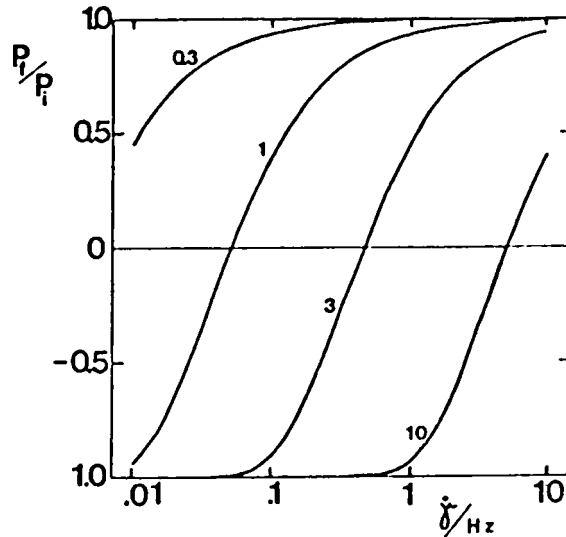
- (i) $\epsilon^2/2\alpha \ll 1$. This means a weak resonance and/or fast crossing and we obtain: $P_f \approx P_i$
- (ii) $\epsilon^2/2\alpha \gg 1$. Here we have a strong resonance and/or slow crossing speed, which results in $P_f \approx -P_i$, that means a complete spin flip will take place.

As mentioned before, imperfection resonances (3a) are caused by radial field components B_r which in turn are related to the vertical closed orbit distortions y . Under certain statistical assumptions, the strength of an imperfection resonance $\gamma G = n$ can be expressed in terms of the rms value of y ⁶:

$$|\varepsilon| \approx n y_{rms} / \pi \langle \beta \rangle \quad (5)$$

where $\langle \beta \rangle$ is the average β function. In Figure 2, the ratio P_f/P_i for crossing of a resonance with $n = 2$ is plotted as function of the "crossing speed" $\dot{\gamma}$ with y_{rms} as parameter. $\langle \beta \rangle = 10$ m has been assumed.

Fig. 2 : The relative polarization P_f/P_i after crossing an imperfection resonance with $\gamma G = 2$ as function of the "crossing speed" $\dot{\gamma}$. The vertical closed orbit distortion y_{rms} (in mm) was taken as a parameter ($\langle \beta \rangle = 10$ m, $\omega_c = 10^7$ Hz).



The two limiting cases of eq.(4) are reproduced, that is $P_f \approx P_i$ for small y_{rms} and fast crossing, and $P_f \approx -P_i$ for large y_{rms} and slow crossing. Only in these cases the magnitude of P is conserved as required; the intermediate region has to be avoided.

A better account for the resonance strength of a given lattice can be obtained by using the computer program "DEPOL" written by E.D. Courant¹³. In addition, the simple picture of resonance crossing is strongly modified by the presence of synchrotron oscillations, which cause multiple resonance crossing^{4, 9}.

For a small storage ring with synchrotron acceleration, where the number of resonances is small, it is not necessary to devise elaborate techniques like pulsed quadrupoles or Siberian snakes, which are used or proposed for the big accelerators^{14, 8}. As for Saturne II, it seems possible to cross the weak resonances quickly without change and the strong ones slowly to perform a proper spin flip¹⁵. Therefore, a flexible system of ramping the magnets of different velocity is required. Using the correction dipoles, the strength of an imperfection resonance can be modified by correcting or amplifying closed orbit distortions in order to optimize the conditions for resonance crossing¹⁵.

Finally, we want to emphasize that for deuterons, there are no depolarizing resonances in the relevant energy range (see Table 1), as the gyromagnetic anomaly is about 12 times smaller than for protons.

STORAGE WITH NON-VERTICAL SPIN DIRECTION

Up to now, we have only considered vertical spin orientation. As mentioned earlier, another spin direction important for the experiment is the longitudinal one.

The most simple idea to produce longitudinal polarization¹⁵ is sketched in Figure 3. The beam with "spin up" is bent vertically by

$$\alpha_b = 90^\circ / \gamma G \quad (6)$$

and becomes longitudinally polarized. Further downstream, the beam is bent by $-2\alpha_b$ and α_b , which restores the original momentum and spin direction. Unfortunately, the necessary bending angle is large for low and medium energy protons and energy-dependent ($\alpha_b=50.2^\circ$ for $\gamma = 1$; $\alpha_b=32.8^\circ$ for 500 MeV). Therefore, this scheme cannot be used as a universal method, in particular if heavy equipment like a spectrometer is needed for the experiment.

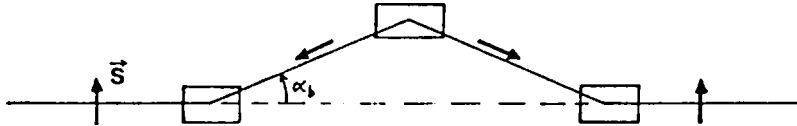


Fig. 3: Simple scheme to obtain longitudinal polarization¹⁵.

Let us now consider a situation where the spin is longitudinal in one straight section of the ring. As we have seen in section 2, this corresponds to a spin resonance. In general, spin resonances can be cured by a Siberian snake^{7, 15, 16}, which rotates the spin around the beam axis by 180° . Consider a ring with two parallel straights and a snake in one of them as shown in Figure 4 for three different spin orientations in the straight opposite to the snake¹⁶.

Only for the longitudinal orientation, the spin vector is stable (lower figure). Therefore, such an arrangement can be used to perform experiments with longitudinal vector polarization¹⁵. The beam has to be injected with longitudinal spin into the straight section or at any other position on the circumference with the local (energy-dependent) spin direction.

For spin-1/2-particles like protons, the vertical and longitudinal spin orientations are sufficient. For particles with spin $> 1/2$ like deuterons ($s = 1$), other orientations are required to measure in particular observables related to the (2nd rank) tensor polarization t_{20} of the beam. The quantity t_{20} is invariant if we invert the spin axis. Going back to Fig. 4, we see that for the other two cases, the spin axis is inverted after each turn, which does not change tensor polarization.

We conclude that, by using a Siberian snake, particles with stable longitudinal vector polarization at the target and with arbitrary (2nd rank) tensor polarization can be stored.

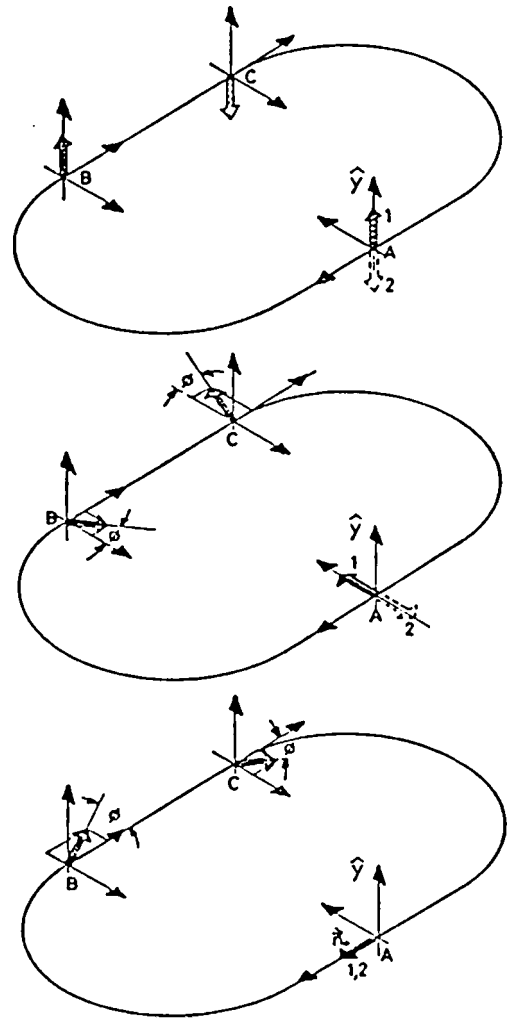


Fig. 4: Principle of the Siberian snake (taken from ref. 16), showing the evolution of spin vector components in one revolution. Section A is field-free, section BC contain the 180° spin rotator.

At low and medium energies, 180° spin rotation can be produced by a solenoid. The spin precession angle is given by

$$\theta_{//} = \theta_0 \frac{B_{//}}{T} \frac{L}{m} \frac{1}{\beta \gamma} \quad (7)$$

where $B_{//}$ is the axial field, L the length and $\theta_0(\text{prot.}) = 51.2^\circ$, $\theta_0(\text{deut.}) = 7.9^\circ$. In Table 2, the $B L$ values for $\theta_{//} = 180^\circ$ are given. Superconducting solenoids are required. Their perturbation of the orbital motion has to be compensated for by additional elements. Such an insertion has been designed for the e^+e^- storage ring VEPP-4 at Novosibirsk¹⁷. It consists of two solenoids with a total maximum field integral of 21 Tm, one normal and four skew quadrupoles.

T/MeV	$B_{\parallel} L / \text{Tesla m}$	
	protons	deuterons
30	0.89	4.11
100	1.67	7.51
300	3.03	13.40
1000	6.37	26.42

Table 2: Integrated solenoid field strength $B_{\parallel} L$ for $\theta_{\parallel} = 180^{\circ}$

ELECTRON COOLING

Two effects might be caused by the electron cooler:

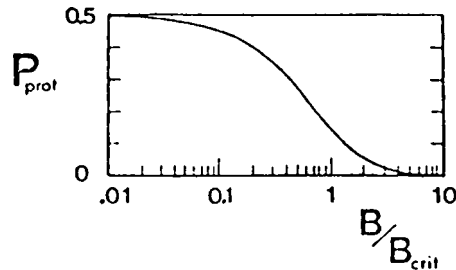
- a) the spin motion is distorted by the longitudinal field B_{\parallel} of the cooler solenoid;
- b) part of the polarization is lost by hyperfine interaction (hfi) with the cooler electrons.

a) If we take $B_{\parallel} L = 0.2 T_m$ for the cooler solenoid, we get from eq.(7) for 100 MeV protons $\theta = 21.6^{\circ}$ per passage for transverse spin direction. This would make a stable spin motion impossible, but of course it can easily be compensated for by an additional solenoid with opposite field direction, as proposed for the IUCF cooler¹. Small compensation errors contribute to the imperfection resonances, which have to be avoided or suppressed anyhow.

b) The question whether there is depolarization due to hfi between electron and nuclear spin is related to the very interesting problem whether one can polarize circulating ions by using polarized electrons¹⁸.

Let us consider an interesting example, where by charge exchange from an optically-pumped Na-vapor target a proton picks up a polarized electron¹⁹. In Figure 5, the calculated proton polarization as function of the external magnetic field is shown. At weak field for full coupling, the polarization approaches 50%. In reality, it is somewhat lower because of electron capture into excited levels.

Fig. 5: Proton polarization as function of external field B (in units of $B_{\text{crit}} = 507 \text{ Gs}$) after hfi of polarized electrons with unpolarized protons (electron ground state assumed).



The important difference to our case is that the system p (or \bar{p}) plus cooling electron is not bound. In fact, in the proton-electron system, with a very small probability, such a "radiative capture" takes place and these neutral hydrogen atoms are lost immediately. But for circulating ions, the interaction takes place only during the very short collision times in the order of 10^{-16} s, which is small compared to the hyperfine period of the H atom (7×10^{-10} s). Thus, a coupling with a subsequent polarization transfer cannot take place.

A possible argument could be that although the interaction is weak, due to the high repetition rate in a storage ring, there might be some net effect. Let us estimate in a very crude model the spin-flip probability of a proton or antiproton by a transverse field $B_{\perp} = 100$ T, which is in the order of the hydrogen 1 s field and which is applied for $t_c = 10^{-16}$ s during each "close collision". For the spin-flip probability, we get:

$$W_{\text{close coll.}} = \sin^2(B_{\perp} t_c \omega/h) \quad (8)$$

which yields $W_{\text{close coll.}} \approx 10^{-13}$ per close collision. If we consider a particle in an electron gas of temperature 10 eV and density $n_e = 3.10^8/\text{cm}^3$, we obtain for the rate of close collisions:

$$\dot{N}_{\text{cc}} \approx 3j_x \sigma_{\text{cc}} \quad (9)$$

with

$$j_x = n_e v_x$$

$$\sigma_{\text{cc}} = \pi a_0^2 \quad (a_0 = \text{Bohr radius})$$

We get $\dot{N} \approx 3/\text{s}$ and for the spin-flip probability per unit time ($n = L_{\text{cooler}}/C \approx 3\%$):

$$dW/dt = n \dot{N} W \approx 10^{-14}/\text{s} \quad (10)$$

From this extremely low number, we conclude that there is no depolarization of the circulating polarized ions by hfi. On the other hand, it can be stated that polarizing circulating ions using polarized electrons is not feasible. Only in the case of circulating paramagnetic ions (that is ions carrying an unpaired electron), one might take advantage²⁰ of the large spin-exchange cross-sections. But it seems doubtful whether the polarization of paramagnetic ions (see Table 1) can be conserved in a storage ring for a sufficiently long time.

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