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STUDIES OF THE SPIN COHERENCE TIME OF PROTONS AT COSY

A. Melnikov*, A. Aksentyev, Y. Senichev
Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia
S. Kolokolchikov, International Union of Pure and Applied Physics, Geneva, Switzerland

Abstract

The search for the Electric Dipole Moments (EDM) of charged particles in storage rings necessitates polarized beams with long Spin Coherence Time (SCT) of the circulating beam. The SCT is the time during which the RMS spread of the orientation of spins of all particles in the bunch reaches one radian. A long SCT is needed to observe the coherent effect of a polarization build-up induced by the EDM. For deuterons the SCT of 1000 s has been achieved at the COoler SYnchrotron COSY (Jülich, Germany). Accomplishing such long SCT for protons is far more challenging due to their higher anomalous magnetic moment, but essential for the planned EDM experiments. It has been shown that for protons the SCT is strongly influenced by nearby intrinsic and integer spin resonances. The strengths of the latter have been calculated for a typical optics setting of COSY and the overall influence on the SCT was predicted. In addition, the efficiency of proton spin flipping with an RF solenoid from initially vertical direction into the ring plane is also investigated.

SCT OPTIMIZATION

A detailed review on optimizing the SCT has been given in [1,2]. It has been shown that in absence of spin resonances spin decoherence can be fully explained by the equilibrium energy shift. For particles with large value of magnetic anomaly G vertical motion is subject to the influence of spin resonances. The latter lead to additional phase space dependent/coherent spin-kicks and finally influence SCT as well. Both these effects need to be considered to optimize the SCT of a beam.

Equilibrium Energy Shift

We note that longitudinal motion is nonlinear in general case. It has been shown in [2] that the solution of nonlinear equations for the principle of synchronous acceleration gives the rise of the average (equilibrium) energy level $\Delta\delta_{eq}$:

$$\Delta\delta_{eq} = \frac{\gamma_s^2}{\gamma_s^2\alpha_0 - 1}\left[\frac{\delta_m^2}{2}\left(\alpha_1 + \frac{3}{2}\frac{\beta_s^2}{\gamma_s^2} - \frac{\alpha_0}{\gamma_s^2} + \frac{1}{\gamma_s^4}\right) - -\frac{\pi}{L_0}\left(\epsilon_x\xi_x + \epsilon_y\xi_y\right)\right]. \quad (1)$$

Here $\xi_{x,y}$ are beam chromaticities and $\epsilon_{x,y}$ are the Courant-Snyder invariants, α_1 is the second order momentum compaction factor. From (1) it can be seen that ξ_x, ξ_y, α_1 have to be optimized to influence nonlinear longitudinal and spin motion. It has been shown in numerical simulations that the shift of a longitudinal phase trajectory vanishes when $\Delta\delta_{eq}$ is minimized. The same is true for the spin-tune deviation [2].

Spin Resonances

Intrinsic resonances are present even in a perfectly aligned machine with periodicity P for $\gamma G = KP \pm Q_y, K \in \mathbb{Z}$. They are caused by a spin perturbation due to a vertical betatron motion. Imperfection resonances occur at integer spin-tunes due to a spin perturbation on an imperfect closed orbit.

One way to predict the influence of spin resonances on the SCT is to calculate their strengths first and to use an analytical model for spin-tune deviations $\Delta\nu_s$. COSY Infinity [3] model of the COSY ring was used in the simulations.

The strengths of intrinsic resonances, ϵ, were calculated using the basic definition: $\epsilon = 1/N_{flip}$, where N_{flip} is the number of turns for the spin to make a full rotation from initial vertical direction. The energy of a particle was fixed and equal to a resonance value. In this situation the invariant spin axis $\vec{n}$ lies in the ring plane [4]. As the strength of intrinsic resonances dpepnds on ϵ_y, particles with different vertical betatron amplitudes at injection were used. Multi-turn particle tracking was performed to investigate the evolution of a spin-vector. One-turn symplectic Taylor map of the ring was used in the simulations.

To estimate the strengths of imperfection resonances the uncorrected imperfect closed orbit was reproduced first (Fig. 1). For this purpose the data for dipole rolls and vertical quadrupole shifts was inserted in the model as for the main sources of horizontal perturbation fields. The resonance strengths were then calculated as Fourier harmonics of spin perturbation:

$$\epsilon_K = \frac{1}{2\pi}(1 + G\gamma)\oint \frac{1}{\chi_m}\frac{\partial B_x}{\partial y} y e^{iK\theta}\, dz. \quad (2)$$

The overall chart of resonance strengths is presented in Fig. 2.

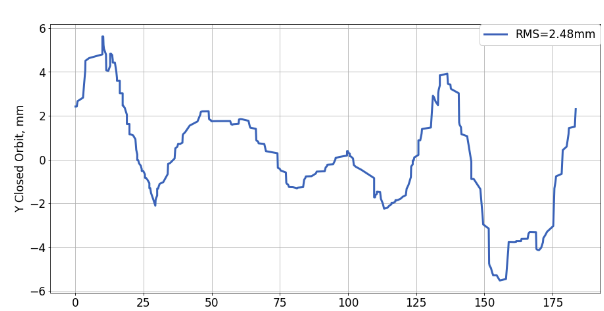

Figure 1: Uncorrected imperfect vertical closed orbit for COSY with $Q_y = 3.7$.

* alexei.a.melnikov@gmail.com

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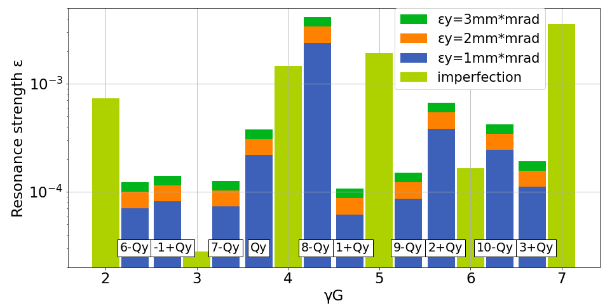

Figure 2: Calculated intrinsic and integer resonance strengths for COSY.

Spin-tune deviations $\Delta\nu_s$ from intrinsic resonances Q_i can be added up analytically for known values of strengths ϵ_i:

$$\Delta\nu_s(\nu_0) = \sum_i \Big[(Q_i - \nu_0) +$$

$$+ sign(Q_i - \nu_0) * \sqrt{(Q_i - \nu_0)^2 + \epsilon_i^2}\Big]. \quad (3)$$

The results for $\nu_0 = \gamma G$ in the energy range of COSY are presented in Fig. 3. They fully reproduce the results from [2]. The latter were obtained with averaging the in-plane spin phase advance during tracking.

From Fig. 3 one can conclude that for the idealized COSY model the strongest effect on $\Delta\nu_s$ comes from the $8 - Q_y$ resonance. The crossing point around $\gamma G = 3$ corresponds to the longest SCT.

Including imperfection resonances in a sum Eq. (3) changes the layout in Fig. 3, but the location of the crossing point stays the same (Fig. 4). This is due to a coherent nature of integer resonances and the increase of a closed orbit length compared to a design value. As a result, particles with different betatron amplitudes have the same spin-tune.

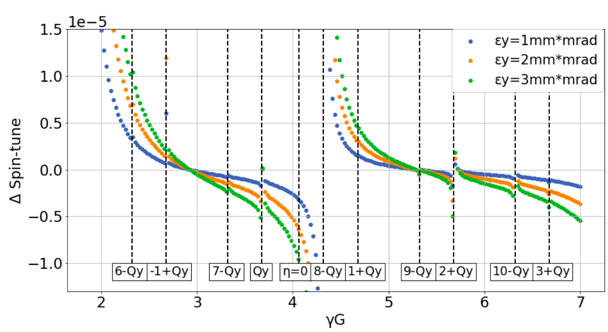

Figure 3: Spin-tune deviations for non-reference particles with different vertical betatron amplitudes; $\xi_y = 0$, for intrinsic resonances only.

SPIN DECOHERENCE ON AN RF SPIN RESONANCE

The first step in conducting a proton SCT experiment at a storage ring is to flip the beam polarization from initially vertical direction into the ring plane. For this purpose at COSY the RF solenoid is used. Preparatory accelerator runs

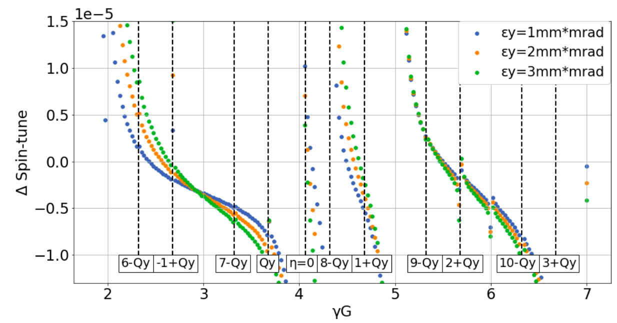

Figure 4: Spin-tune deviations for non-reference particles with different vertical betatron amplitudes; $\xi_y = 0$, for intrinsic + integer resonances.

with protons show that high ratio of anomalous magnetic moments of proton and deuteron $G_p/G_d \sim 13$ means fast proton spin decoherence during the flip. Therefore, the task of increasing the in-plane polarization after the flip is mandatory for preparation of proton SCT experiments and needs detailed investigation.

The general theory of spin decoherence during the RF spin flip is presented in Ref. [5]. Here we recall the basic laws.

In the case of a static spin-rotator the in-plane polarization $S_\perp$ transfered from vertical S_y in a single pass is: $S_\perp = S_y \cdot \alpha$, $\alpha = const$. Taking into account the phase of the RF field of a solenoid and the phase of a spin motion for n turns we get:

$$S_\perp(n) = S_y \cdot \alpha \sum_{l=1}^{n} \cos(l\theta_s)\cos(l\theta_f) =$$

$$\frac{1}{2} S_y \cdot \alpha \sum_{l=1}^{n} \cos(l(\theta_s - \theta_f)) + \cos(l(\theta_s + \theta_f)), \quad (4)$$

where $\theta_s = 2\pi\gamma G$, $\theta_f = 2\pi f_{RF}/f_{rev}$. Resonance action on polarization takes place when $\theta_s \pm \theta_f = 2\pi K, K \in \mathbb{Z}$, or for the frequency value of the spin-rotator f_{RF}:

$$f_{RF} = K f_{rev} \pm \gamma G f_{rev}. \quad (5)$$

In the presence of an RF cavity there is an oscillating part of the spin-tune $2\pi G\delta\gamma$. Consequently, for particles with momentum offset there is a cumulant spin precession slip $\Delta(n)$. Then Eq. (4) can be rewritten as:

$$S_\perp(n) = S_y \cdot \alpha \sum_{l=1}^{n} \cos(l\theta_s + \Delta(l)) \cdot$$

$$\cdot \cos\left(l\theta_f + \frac{f_{RF}}{\gamma G f_{rev}} \frac{\eta}{\beta^2} \Delta(l)\right) = \frac{1}{2} S_y \cdot \alpha \sum_{l=1}^{n} \cos(C_{SD}\Delta(l)), \quad (6)$$

where the spin decoherence factor C_{SD} is:

$$C_{SD} = 1 - \frac{\eta}{\beta^2}\left(1 + \frac{K}{G\gamma}\right). \quad (7)$$

From Eq. (6) it is evident that the signal of in-plane polarization is maximized when $C_{SD} \to 0$. In this case the RF

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solenoid and spin precession phase slips are compensated and the decoherence during the flip is suppressed.

One can also show that the SCT during the flip can be written in the form [5]:

$$\tau_{SC} \sim \frac{1}{C_{SD}^2 G^2 \delta^2}, \tag{8}$$

where δ is a RMS relative momentum spread dp/p of the beam.

These basic features of RF spin decoherence were verified in the numerical experiment in COSY Infinity [3] software.

For each n-th turn the action of the RF solenoid is modeled as a rotation of a spin-vector of each particle in the beam around a longitudinal axis at an angle ϕ_{rot}:

$$\phi_{rot} = \frac{(G+1)BL_{sol}}{\chi_m} \cdot \cos\left[2\pi f_{RF}(n * T_{rev} + \Delta t(n)) + \phi_0\right], \tag{9}$$

where the revolution period is $T_{rev} = 1/f_{rev}$, $\Delta t(n)$) is a lag of an arrival time to the solenoid for each individual particle, ϕ_0 is an initial phase offset.

The typical machine parameters for the experiment are: $T = 140$ MeV, $BL_{sol} = 0.12$ T·mm, $f_{syn} = 330$ Hz, $K = -1$. The pre-cooled beam is characterized with $\delta = 3 \cdot 10^{-4}$, $\epsilon_y = 2$ mm·mrad. For the cooled beam: $\delta = 5 \cdot 10^{-5}$, $\epsilon_y = 0.5$ mm·mrad. Typically the e-cooler system is switched off about 10 s prior to the flip. It is done in order to set up an orbit not disturbed by the cooler magnets. For this reason the pre-cooled beam is considered. The choice of the beam energy is motivated by the possibility to use the e-cooler in this range.

From Eq. (7) it is evident that the choice of the RF solenoid harmonics K strongly influences the spin decoherence. The latter was confirmed in the simulations for the pre-cooled beam (Fig. 5). As predicted by the theory, $K = -3$ is the best choice in terms of spin decoherence, where C_{SD} is minimal.

As the RF solenoid phase slip for individual particles is mostly determined by δ, one can note strong dependence of τ_{SC} on this parameter in Eq. (8). It was also observed in the numerical experiment (Fig. 6). Since the dependence on δ is strong, it is recommended to run with a continuous cooling.

As the beam energy $T = 140$ MeV corresponds to $\gamma G = 2.06$, one can observe from Fig. 3 the effect on $\Delta\nu_s \sim 10^{-5}$ from spin resonances. The latter act as an additional source of spin decoherence during the flip (Fig. 7).

CONCLUSION

The first step in optimizing SCT of a beam is to tune ξ_x, ξ_y and α_1. The next step is to take into account the influence of integer and intrinsic spin resonances, which come into play especially for a proton beam. An analytic approach based on the information of resonance strengths allows to estimate this effect. For intrinsic resonances only we obtain, that the crossing point around $\gamma G \sim 3$ is the most suitable for the proton SCT experiment. This working point showed to be robust after consideration of integer resonances also.

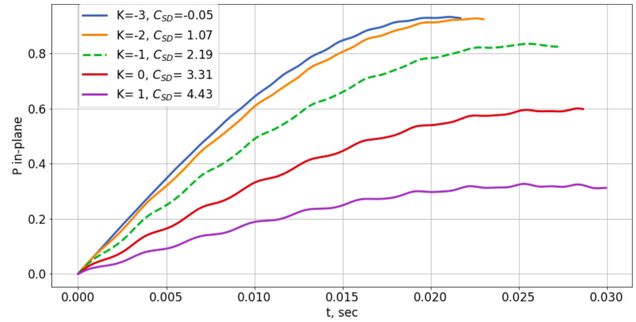

Figure 5: Evolution of the in-plane polarization during the time of the RF flip for different harmonics K.

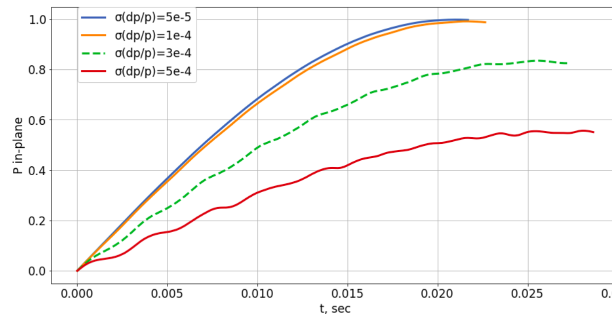

Figure 6: Evolution of the in-plane polarization during the time of the RF flip for different values of δ of the beam.

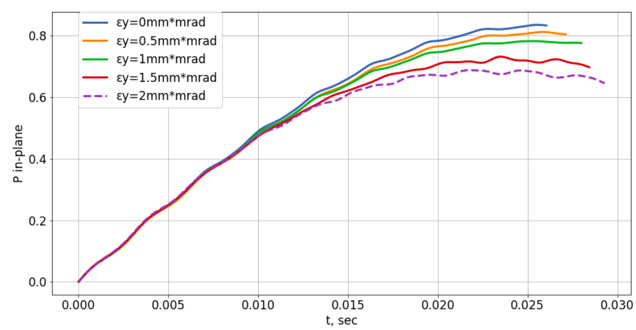

Figure 7: Evolution of the in-plane polarization during the time of the RF flip for different values of ϵ_y of the beam.

The investigation of methods to decrease proton beam depolarization during the RF spin flip revealed two key points:

- One has to choose harmonics K in order to minimize C_{SD};
- Strong dependence of τ_{SC} on δ demonstrates the necessity of beam cooling.

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