IDEAS FOR LONGITUDINAL POLARIZATION AT THE Z/W/H/TOP FACTORY

I. A. Koop†[1,2], A. V. Otboev, Yu. M. Shatunov[1],
Budker Institute of Nuclear Physics, [630090] Novosibirsk, Russia
[1]also at Novosibirsk State University, [630090] Novosibirsk, Russia
[2]also at Novosibirsk State Technical University, [630090] Novosibirsk, Russia

Abstract

Different schemes for getting the longitudinal polarization at FCC-ee are considered. Depolarization rates for rings with spin rotators are evaluated and methods of acceleration of polarized beams in a booster synchrotron are proposed.

INTRODUCTION

First ideas on how the stable longitudinal polarization of colliding electrons and positrons can be achieved were proposed in 70-th [1–4]. In this paper we analyse the possibilities to use 90^0 spin rotators which are installed at proper bending angle relative to the Interaction Point (IP) of the FCC-ee collider [5].

The crab-waist collision scheme assumes an operation with extremely small vertical beam emittance. Therefore only the solenoid type spin rotators with a compensated *x–y* coupling can be used for spin manipulations in a ring. Also due to strong Synchrotron Radiation (SR) and associated with that fast energy diffusion the schemes which utilises the idea of Siberian Snake can't be used. Restoration of the vertical spin direction in main arcs of FCC-ee is mandatory. Only then the spin-orbit coupling effects and the depolarization rates are minimised to the acceptable level.

LONGITUDINAL POLARIZATION

Near the *Z*-peak (beam energy around 45.6 GeV) the spin tune $\nu_0 = \gamma a$ is equal to $\nu_0 = 103.5$. Here γ is the Lorentz factor and $a = q'/q_0 \simeq 0.0016$ states for the anomalous magnetic moment of an electron. Hence, if spin is directed longitudinally at IP, it shall be rotated two times by 90^0—first by a bend in the horizontal plane and then by a solenoid around the longitudinal axis, see Fig.1.

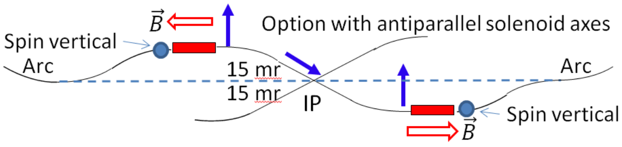

Figure 1: The proposed spin and velocity rotation sequences for achieving the longitudinal polarization at Z.

The corresponding velocity vector bending angle is $\phi = 0.5\pi/\nu_0 \simeq 0.015$, while the needed longitudinal field integral is $BL = 0.5\pi BR/(1+a) \simeq \pm 235$ T·m per rotator. Remind, that due to antisymmetric layout of all spin rotations in this scheme, the net spin rotation is zero. Therefore the equilibrium spin direction in main arcs is the same as without spin rotators and, moreover, it is independent on the particle's energy. This is very important, because guaranties the cancelation of spin-orbit coupling in arc's dipole magnets. Spin direction is chromatic only in the chicane magnets, which rotate spin in the horizontal plane. But their contribution to radiative depolarization by quantum fluctuations of SR is negligible. Another remark: the global spin precession frequency is not affected by such an insertion and can be used for beam energy determination applying the Resonant Depolarization (RD) method.

Unfortunately, the accumulated bending angle distribution in FCC-ee experimental straight section is not fully antisymmetric relative to IP—at the left side bends with negative curvature are much weaker compared to bends on the right side from IP, see Fig.2.

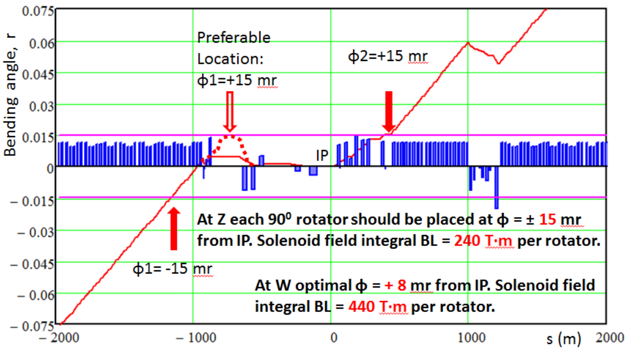

Figure 2: The accumulated bending angle distribution in FCC-ee experimental straight section (red solid curve). The dotted curve shows the desirable bending angle dependence optimal for the operation with longitudinal polarization at *Z*. The alternative place for inserting of the left side spin rotator is $\phi 1 = -15$ mr—seems easier for realization.

Therefore, for realization of the discussed above the ideal spin rotation scheme shown in Fig.1, the geometry of bends on the left side of the straight section should be changed so, as to provide empty drifts at $\phi = +15$ mr from IP. This is schematically shown in Fig.2 by the dotted red line. The alternative place for inserting the left side spin rotator, shown at Fig.2 by the red arrow, is $\phi = -15$ mr. This option, probably, is easier for realization, because all changes in the ring layout should be done at much larger distance from IP, thus not affecting the background problems from SR near detector. In this option the angle between axis of the left and the right rota-

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[†] koop@inp.nsk.su

tors is near ϕ=30 mr and, correspondingly, spin makes half turn around the vertical axis by such bend between rotators at some specific spin tune, say at $\nu_0 = 101.4$. The difference in depolarization rates between two options is not large. At the Fig.3 are plotted the dependences of modules of the spin-orbit coupling vector $d = |\gamma \partial \vec{n} / \partial \gamma|$ on the spin tune for two discussed above layouts: with zero integral bend between rotators and with ϕ=31 mr (spin rotation is exactly by π at $\nu_0 = 101.4$). In both cases the same spin perturbation w=0.01 is introduced at some ring azimuth. There one can see many minimums, roughly $d = 10 \div 12$, near half-integer spin tunes—optimal energy points for preserving beams polarization.

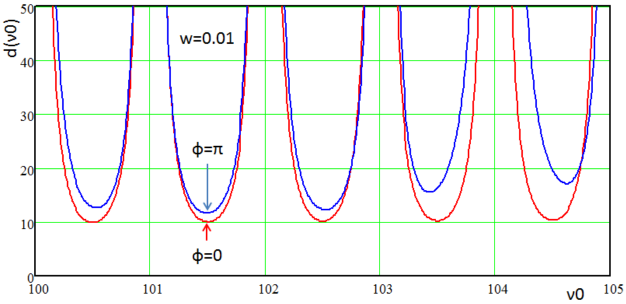

Figure 3: Module of the spin-orbit coupling vectors in arcs of FCC-ee for two options: spin rotations by bends between left and right spin rotators are ϕ =0 and ϕ =π at $\nu_0 = 101.4$. In both cases the same spin perturbation w=0.01 is introduced at some ring azimuth.

The depolarization rate τ^{-1} depends on the average value of the d-factor as [6]:

$$\tau^{-1} = \tau_{ST}^{-1} \left(1 + \frac{11}{18} d^2 \right),$$

where $\tau_{ST} = 260$ hours at Z is the Sokolov-Ternov self-polarization time. Obviously we can reduce it, say, to $\tau = 0.5 \div 1.5$ hours—the expected luminosity life-time. Hence, the permissible value of the d-factor is about $d = 17 \div 30$, correspondingly the spin perturbation value should not exceed $w = 0.017 \div 0.03$. This goal can easily be reached applying the well-known harmonic spin matching technique [7, 8], because even with $\sigma_Q = 50$ µm the average accuracy of quadrupole lenses alignment reaches only w=0.02 according our estimations.

MAKING BEAMS POLARIZED

The injector chain of FCC-ee consists of 6 GeV linac, conversion system to produce positrons, two 1.54 GeV damping rings for cooling electrons and positrons, 6–20 GeV pre-booster synchrotron and finally the main booster synchrotron for acceleration of beams from 20 up to 182.5 GeV [9].

The polarized electron beam of full intensity can be achieved from the polarised electron gun, as it was already demonstrated in many labs, experiments and proposals. Here we will discuss only a problem of how a positron beam can be made polarized via the Sokolov-Ternov mechanism in a special wiggler-ring with asymmetric bending fields. An example of parameters for such storage ring is presented in the Table 1.

The radiative polarization time is inverse proportional to fifth power of beam energy and cubic power of the modulus of an orbit curvature [4]:

$$\tau_p^{-1} = \frac{5\sqrt{3}}{8} \lambda_e r_e c \gamma^5 \left\langle |K|^3 \right\rangle .$$

Obviously, to get a short polarization time it is desirable to use very high average bending field and choose beam energy as high as possible. In our example we consider the racetrack ring comprised with two 25 m arcs and two 5 m straight sections. Each of 20 FODO cells is comprised of 4 asymmetric wigglers. The positive $B1$=10.5 T pole has a length $L1$=10 cm, while two negative poles of a wiggler have the field $B2$=−1.796 T and a length $L2$=−18 cm. Each wiggler bends beam by 4.5^0.

Table 1: Preliminary Specifications of Polarizing Positrons Wiggler-Ring

Parameter	**Value**	**Dimension**
Beam energy, E	1.54	GeV
Circumference, C	60	m
Bending radii: $r1$, $r2$	0.49, −2.86	m
Bending fields, $B1$, $B2$	10.5, −1.8	T
Energy loss/turn, ΔE	2.925	MeV
Momentum spread, $\sigma_{\Delta E/E}$	0.00166	
Bunch population, N	$2 \cdot 10^{10}$	
Number of bunches, N_b	20	
Bunch spacing, Δt	10	ns
Total beam current, I	0.32	A
SR power, P	937	kW
RF frequency, f_0	400	MHz
RF harmonic number, h	80	
RF voltage, V_{RF}	4	MV
Bucket size, $A_{\Delta E/E}$	1	%
Synchrotron tune, ν_s	0.0235	
Bunch length, σ_s	16.5	mm
Polarization time, τ_p	9.8	s
Polarization degree, P	77.5%	after 20 s

In such a ring 77.5% polarization degree will appear in 20 seconds (after two polarization time), while the asymptotic polarization level is 89%.

A sequence of injections/extractions looks as follows. A fresh, unpolarised bunch of positrons is extracted every second from the low emittance 1.54 GeV damping ring and injected into the wiggler-ring. There each bunch is becoming polarized being stored in this ring for 20 s, or approximately for two polarization time. After that the polarized bunch is returned to the main damping ring for cooldown, simultaneously be replaced by a new unpolarized bunch from it. Assuming the beam lifetime

$\tau_{beam} = 4000$ s and the production rate $\dot{N}_{e+} = 2\cdot 10^{10}$ positrons per second, we can store in the collider ring 500 of the full intensity bunches with the nominal bunch population $N = 1.7\cdot 10^{11}$ positrons per bunch. This corresponds to a luminosity of $L = 0.7\cdot 10^{35}$ cm^{-2} s^{-1} for experiments with doubly polarized beams near Z-peak. But FCC-ee collider can handle up to 16640 bunches of such intensity. So, all extra collisions, beyond of 500 doubly polarized, will proceed in the un-polarized mode, or with polarized electron bunches only.

To reach the higher luminosity, one should increase the ring circumference and proportionally the number of wigglers. This looks at first glance not very reasonable but more difficult for realization.

ACCELERATION OF POLARIZED BEAMS IN A BOOSTER

Let's now discuss problems of how one can preserve polarization during acceleration of beams in the main booster synchrotron. The nominal ramping speed is 25 GeV in 0.32 s, or equivalently: $d\nu/dN = 0.056$ spin rotations per turn. We have performed the spin tracking simulations of how polarization will be lost during the acceleration process. First option, presented on Fig.4, assumes fast crossing of many integer resonances in presence of a local spin perturbation with some reasonable strength w=0.02. We limit the range of spin tune ramp by the diapason $89 < \nu_0 < 104$. One can see that polarization loss for this option is unacceptably high—each crossing of integer resonance kills about 10–20 % of the polarization degree.

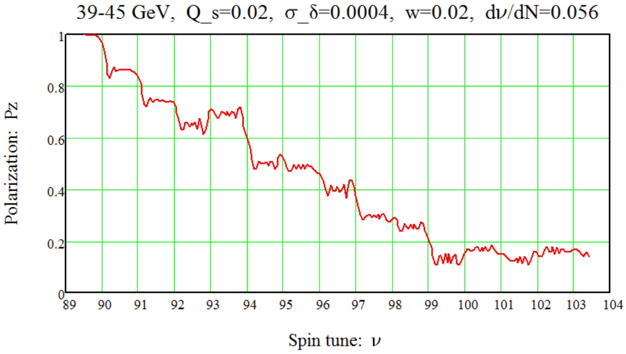

Figure 4: Drop of beam polarization during "fast" crossing of many integer resonances. Local spin perturbation is chosen *w*=0.02.

The second option assumes acceleration in presence of a weak Partial Snake. Results of same simulations are shown in Fig.5. In this option all spins are reversing coherently their vertical component when crossing each integer resonance and polarization is preserved quite well. On our opinion this option is most favourable for acceleration up to *Z* peak. Solenoids of a snake can be kept static, while all quads inside the snake's insertion will be ramped in such a way, that matrix of the insertion will be kept constant and fully uncoupled. The need longitudinal field integral is about $BL = 200$ T·m. Then at 20 GeV we will have *w*=0.5 (full snake!) and *w*=0.22 at 45.6 GeV.

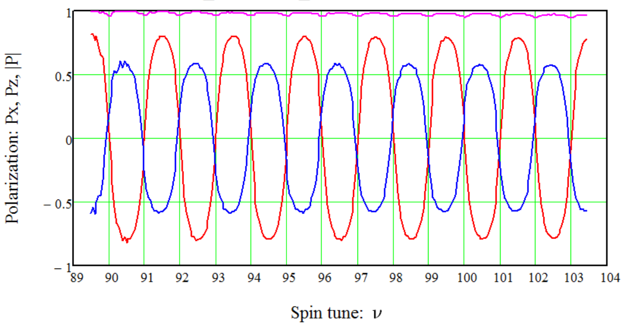

Figure 5: Acceleration in a booster ring with Partial Snake strength *w*=0.2. Polarization loss is only 3.5%.

Unfortunately, the Partial Snake scheme does not work for beam acceleration up to *W* threshold. Then beam is subjected to rather fast depolarization. For this energy interval is mandatory to avoid any crossing of integer resonance. Also *d*-factor should be as small as possible—means spin should be vertical in arcs. All this is accomplished in a third option [10–11], which assumes preservation of polarization with the use of even numbers of full Siberian Snakes. They divide a booster ring in unequal bending arcs, see Fig.6. Stable spin direction is vertical everywhere, but changes the sign after passing through each snake. The global spin tune became very low in this option. For example: with the asymmetry parameter $\chi = 0.002$ the spin tune reaches the value $\nu = \chi\nu_0 = 0.363$ for $\nu_0 = 181.5$ (*E*=80 GeV).

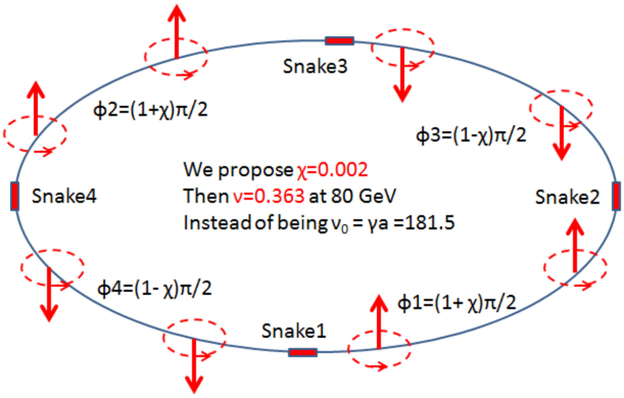

Figure 6: Four Siberian Snakes divide a ring in four unequal arc segments. The stable spin direction is vertical and changes a sign after each Snake.

This makes possible acceleration of polarized beams up to very high energy, say up to 80 GeV. The only problem now is that all solenoids should be ramped proportionally to the beam energy. That is an issue, which we leave for future technical studies. As an example, beam depolarization at 80 GeV induced by high localized spin perturbation *w*=0.1 is shown on Fig.7.

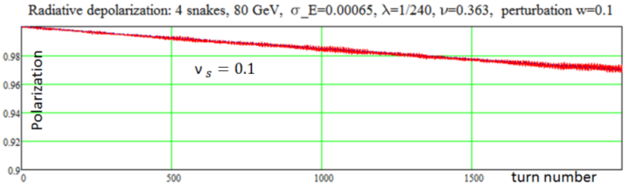

Figure 7: Spin tracking results for study of beam depolarization at 80 GeV ring with 4 Siberian Snakes. Spin perturbation value is *w*=0.1.

The observed depolarization time 18 s is sufficiently large and a polarized beam can be accelerated in 10 s without significant loss of the polarization from 20 GeV up to 80 GeV.

SOLENOID TYPE SPIN ROTATORS

Most robust lattice design of the solenoid type spin rotators is presented in the Fig.8.

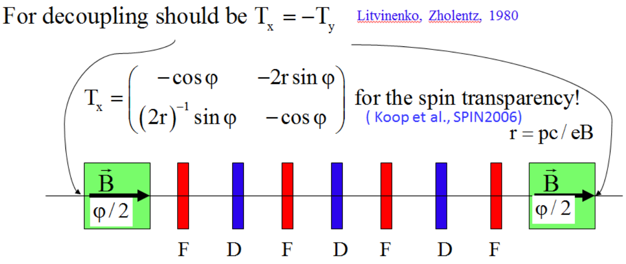

Figure 8: Optimal scheme of the solenoid type spin rotators.

Two identical solenoids and 7 quadrupole lenses in between comprise an insertion with the specified optical properties. Namely, their two-dimensional matrix blocks should satisfy the condition $T_y = -T_x$ to cancel *x-y* coupling [12]. Moreover, for spin transparency it is desirable to fulfil one extra condition [13]:

$$T_x = -T_y = \begin{pmatrix} -\cos\varphi & -2r\sin\varphi \\ (2r)^{-1}\sin\varphi & -\cos\varphi \end{pmatrix}, \quad r = Br/B$$

Seven quadrupole lenses, combined into four families, provide very good flexibility for achieving of the desired transformation properties of the insertion optics. It is remarkable that all quads in this scheme don't need to be made of skew type! The required optical solution can be found practically for any arbitrary solenoid strength. In particular, solenoids can be switched off, if polarization not needed at all.

CONCLUSION

At *Z* the longitudinal polarization looks feasible, but some changes in IR lattice are required to insert rotators at $\phi = \pm 15$ mr from IP.

At *W* both rotators should be moved to other drifts located at $\phi = \pm 8$ from IP. Depolarization rate will be roughly the same as without spin rotators, if their axes are parallel each other, and will be slightly higher, if the left side rotator will be placed at negative bending angle $\phi = -8$ mr.

In any case fast acceleration of pre-polarized electron and positron beams has to be foreseen. Partial Snake with static solenoids will preserve polarization during ramping up to *Z*-peak energies. But acceleration up to *W* requires use of few Siberian Snakes installed in the main booster.

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