Longitudinally polarized electrons in Novosibirsk c-tau factory

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Abstract.
We consider a scenario for achieving and preserving the longitudinal polarization of the electron beam in the Novosibirsk tau-charm factory. The storage ring for electrons will be equipped with 5 spin rotators - the so-called Siberian Snakes. These Snakes strongly reduce the spin-orbit coupling and, thus, suppress the depolarization of the electron beam caused by quantum fluctuations of the synchrotron radiation. The proposed scheme provides a high polarization degree up to 80% - 90% in the full energy range.

1. Introduction
In the Novosibirsk tau-charm factory (CDR is under preparation) electron and positron beams shall collide with equal energies; no asymmetry of the energies of the two beams is required. Each beam energy shall vary from 1 GeV up to 2.5 GeV. The luminosity of the factory shall be not less than $10^{35}$ cm$^{-2}$s$^{-1}$ in the high energy region and in the order of $10^{34}$ cm$^{-2}$s$^{-1}$ in the low energy one. The electron beam shall be polarized longitudinally at the interaction point (IP).

For this purpose a source of polarized electrons is allowed for in the design, at the exit from which one can get any spin direction and thus, with all future rotations, at the point of injection the beam will have the correct spin direction.

Two alternatives for obtaining the longitudinal polarization at the IP of the base ring were considered: (1) a scheme with restoration of the vertical direction of spin in the main part of the arc and (2) a scheme using Siberian Snakes. In the first case two spin rotators are used, which are located near the IP. They perform 90° spin rotation around the longitudinal axis at some specific energy. Besides spin precess by 180° around the vertical direction of the magnetic field of few bending magnets located in between of two spin rotators (a short arc with IP in its middle). In this case, the spin rotators occupy a relatively small space and the integral of the longitudinal field is small, which is a positive moment in terms of the betatron coupling. A significant drawback of this scheme is the presence of three spin resonances in the working energy range, one of which falls on the point of τ-lepton production, and the other, on the Λ-baryon region. That is why the second scheme was chosen. However, to obtain a high degree of polarization throughout the energy range, there must be not a single but 3 or 5 Siberian Snakes.

2. Tau-charm factory layout
Subject to the above, the $c\tau$-factory comprise of the following facilities:
- Injector of positrons
- Polarized electrons injector
- Full energy linear pre-accelerator
- Double-ring collider

Two independent (electron and positron) injectors can effectively produce particles without losing time for changing the polarity of the magnets and implement the scheme of simultaneous acceleration of two bunches. The linear accelerator (unlike the synchrotron) allows accelerating the polarized particles without losing the degree of polarization as well as accelerating large charges of particles with smaller loss and higher repetition frequency.

The main ring of the \(c\tau\)-factory is a racetrack storage ring consisting of arcs, the technical straight-section for injection and the experimental section (shown schematically in Fig. 1).

![Schematic of the Novosibirsk \(c\tau\)-factory.](image)

The arcs comprise four Siberian snakes alternating with four superconducting wigglers. The parameters of the arcs were chosen so as to obtain the required dimensions and radiation parameters of the beam. The optics of the periodicity elements must ensure the expected beam emittance. At 2.5 GeV the damping time should be 30 ms and the beam emittance should be 8 \(\text{nm} \cdot \text{rad}\) with the wigglers turned off. The technical straight section accommodates the accelerating RF-system, the fifth Siberian snake and the injection equipment. In the midpoint of the technical straight section a vertical separation of the beams is arranged. The experimental straight section is intended to focus the beams at the IP.

The main parameters of the collider are presented in Table 1.

3. Snakes and closed spin orbit
The idea of making the equilibrium spin direction being longitudinal at IP using Siberian snake, placed at the opposite to IP azimuth, was proposed by Derbenev and Kondratenko [1, 2]. We suggest to install on the electron ring of 5 such snakes. Each snake rotates spin by 180° around the direction of particle’s velocity.

With an odd number of snakes, uniformly distributed along the ring, the spin in the arcs lies in the median plane and takes exactly the longitudinal direction in the middle of the arcs between the snakes, see Fig. 2. So, one of these devices should be placed exactly just opposite
The Novosibirsk $\eta$-factory parameters.

| Parameter                              | Value 1.0-2.5 GeV |
|----------------------------------------|-------------------|
| Energy                                 | 1.0-2.5 GeV       |
| Circumference                          | 765 m             |
| Crossing angle                         | 60 mrad           |
| Emittances, $\epsilon_x/\epsilon_y$    | 8/0.04 nm         |
| Number of bunches                      | 390               |
| Number of particles/bunch              | $7 \cdot 10^{10}$ |
| One beam current                       | 1.7 A             |
| Beta functions, $\beta_x/\beta_y$      | 4 / 0.08 cm       |
| Beam sizes at IP, $\sigma_x/\sigma_y$  | 18 / 0.18 mkm     |
| Luminosity                             | $(0.6 - 1.0) \cdot 10^{35} cm^{-2} s^{-1}$ |
| Longitudinal polarization (electrons)  | $\pm(80\% - 90\%)$ |

Figure 2. The equilibrium closed spin trajectory in the ring with 3 Siberian snakes. The depolarizing influence from the damping wigglers is minimal if they are situated in those places where the spin is longitudinal.

Figure 3. Optical functions of the spin-rotator - the Siberian snake, which rotates the spin through $180^0$ around the axis of the solenoids.

to the IP to provide the stable longitudinal direction of a spin at the interaction region and the others should be equally spaced by the velocity rotation angle $2\pi/5 = 72^0$.

Technically each snake comprise two solenoids separated by a set of quads (see Fig. 3). The total longitudinal field integral is equal to:

$$\int B_s ds = \pi B \rho = 26 T \cdot m, \ for E = 2.5 GeV$$

(1)

The transport matrix of the spin rotator, including the solenoids, must comply with the following two conditions: 1) zero $2 \times 2$ off-diagonal blocks (zero coupling) and 2) spin transparency. Both these requirements are met for a full Siberian snake if [4]
where $\varphi$ is the angle of spin rotation by one solenoid and $r = B\rho/B_s$. For a full snake, $\cos(2\varphi) = -1$. If $\varphi < \pi/2$, the snake is called partial. Unfortunately, it yields to a full one in respect of providing a shorter depolarization time and will not be considered here.

The spin transparency of a snake ensures the cancelation of the betatron part of the spin-orbit coupling in the arcs. Owing to this property the depolarization of the electron beam, caused by the emission of the synchrotron radiation, will be suppressed to a minimal level.

A method of compensation of the solenoid-introduced betatron coupling via inserting the optical system meeting the condition $T_x = -T_y$ between the solenoids was proposed in [5]. A big advantage of this method is no need to use any skew-quadrupoles. In this scheme the solenoid field may vary in a wide range without changing the strength of the quadrupole lenses, including their complete switching off, the coupling remaining zero in this case. Though, if one wants to leave the advance of the betatron phases unchanged throughout the insert, the field gradient in the lenses still have to be slightly corrected. Most important is that there is no need to rotate the lenses around the longitudinal axis in contrast to some alternative schemes of compensation of coupling also considered in [5]. The Fig.3 shows the optical structure, the beta-functions and the dispersion function of the $c\tau$-factory’s snake.

4. Radiative relaxation of spins

When a particle at azimuth $\theta$ emits the synchrotron radiation quantum its energy changes suddenly and due to this its equilibrium spin direction $\vec{n}$ jumps also. The spin direction chromaticity $\vec{d}(\theta) \equiv \gamma (\partial \vec{n} / \partial \gamma)$ is proportional to the spin tune $\nu_0 = E(\text{GeV})/0.440652...$ and to the arc length $\Delta \theta = 2\pi/n_{\text{snk}}$. The larger the number of the snakes installed on the ring, the greater the depolarization time reached. The depolarization time increases quadratically with the number of the snakes. We chose five snakes providing perfect preservation of the electron beam polarization across the energy range. At low-energy operation it is possible to use smaller number of snakes, one or three. The analytical estimates of the azimuth-averaged squared modulus of the vector of the spin-orbit coupling for a ring with $n_{\text{snk}}$ snakes give the following result

$$\langle \vec{d}^2(\theta) \rangle = \vec{d}^2(0) + \frac{\pi^2}{3} \frac{\nu_0^2}{n_{\text{snk}}^2}$$

$$\vec{d}^2(0) = \frac{\pi^2}{4} \sin^2 \frac{\pi \nu_0}{n_{\text{snk}}}$$

Here $\vec{d}$ is the spin-orbit coupling vector, $\vec{d}^2(0)$ is the squared modulus of it at the minimum point, $\langle \vec{d}^2(\theta) \rangle$ is its value averaged over the arc length. The azimuthal dependence of the $\vec{d}^2(\theta)$ for the cases $n_{\text{snk}} = 1$ and $n_{\text{snk}} = 3$ for the electron energy $E = 1 \text{ GeV}$ is presented in Fig. 4.

Knowing the behavior of $\vec{d}$ in the ring, it is easy to calculate the time of radiative spin relaxation as well as the equilibrium degree of the radiative polarization. They are determined from the known formulas by Derbenev and Kondratenko [3]
\[ P_{\text{rad}} = -\frac{8}{5\sqrt{3}} \left| r \right|^{-3} \left( 1 - \frac{2}{9} (\vec{n} \vec{v})^2 + \frac{11}{18}\vec{d}^2 \right) \langle |r|^{-3} \left( 1 - \frac{2}{9} (\vec{n} \vec{v})^2 + \frac{11}{18}\vec{d}^2 \right) \rangle \] (5)

\[ \tau_{\text{rad}}^{-1} = \frac{5\sqrt{3}}{8} \lambda_{e} r_{e} c \gamma^{5} \left| r \right|^{-3} \left( 1 - \frac{2}{9} (\vec{n} \vec{v})^2 + \frac{11}{18}\vec{d}^2 \right) \langle |r|^{-3} \left( 1 - \frac{2}{9} (\vec{n} \vec{v})^2 + \frac{11}{18}\vec{d}^2 \right) \rangle \] (6)

Here \( r \) is the curvature radius of the orbit in the dipole magnets, \( \vec{b} \) is the unit vector directed along the field in these magnets, \( \vec{v} \) is the unit vector directed along the velocity, \( \vec{n}, \vec{d} \) are the vectors defined above, and the rest designations are standard.

At the \( c\tau \)-factory the wigglers are supposed to be used for the regulation of the radiative damping decrements, namely, to maintain the damping time of around 30 ms in the entire energy range of the complex. At low energy near 1 GeV the wigglers are turned on for the maximum field, while at the maximum energy near 2.5 GeV the wigglers are completely turned off. When calculating the time of depolarization in the storage ring, it is necessary, of course, to consider the influence of the wigglers on this process. As seen in Fig.4, the contribution of the damping wigglers strongly depends on the place of their location. If they stay in such segments of the ring, where the modulus of the spin-orbit coupling is minimal (in the middle of the arc between the two snakes), their effect is negligible. If they are distributed evenly over the ring, their influence is quite palpable.

5. Time averaged degree of polarization

With the Siberian snakes on the ring, the equilibrium degree of radiative polarization of the beams almost vanishes. This is the positive moment because a definite sign of the beam self-polarization may lead to systematic errors in the analysis of the spin asymmetry of the processes of interest. It is planned to randomly inject several (up to few hundreds) bunches of polarized electrons into different separatrices and mark all the recoded events with the number of separatrix they correspond to.

The loss of particles occurring mainly due to the bremsstrahlung on the counter beam, of course, must be made up with the fresh-polarized electrons. As a result, some equilibrium polarization degree determined by the balance of particles surviving in the ring for different times will establish gradually. It is easy to show that the equilibrium polarization degree is equal to

\[ P = \frac{P_{\text{beam}}}{\tau_{\text{beam}} + \tau_{\text{rad}}} \frac{\tau_{\text{rad}}}{\tau_{\text{beam}} + \tau_{\text{rad}}} + \frac{P_{\text{rad}}}{\tau_{\text{beam}} + \tau_{\text{rad}}} \frac{\tau_{\text{beam}}}{\tau_{\text{beam}} + \tau_{\text{rad}}} \] (7)

Here \( P_{\text{beam}} \approx 90\% \) is the degree of polarization of the fresh beam, \( P_{\text{rad}} \approx 0 \) is the degree of the radiative self-polarization of electrons in the ring, \( \tau_{\text{beam}} = 1000 \text{ sec} \) is the lifetime of the particles in the ring and \( \tau_{\text{rad}} \) is the time of the radiative polarization of the spins. Fig. 5 presents the plots of the time-averaged degree of electron beam polarization for 1, 3 and 5 snakes. These results were obtained analytically and confirmed by computations with the ASPIRRIN program [6, 7]. It is seen from the figure that the variant with 5 snakes ensures the polarization degree of about 80% across the accelerator energy range.

6. Technical aspects of the realization of spin rotators

A set of two superconducting solenoids and seven quadrupole lenses should be created for each of the spin rotators. One solenoid is 2 m long and has a maximum field of 6.5 Tesla and a 4 cm aperture. It seems that a solenoid with such parameters can be cooled to a 4.5 K temperature
with a three-stage cooler and placed in just a vacuum cryostat without liquid helium. Such experiments using indirect cooling of small superconducting devices are currently under way at BINP.

The total length of one Siberian snake is about 10 m, or about 1.5% of the entire perimeter. All the quadrupole lenses have the same specifications as the main lenses of the ring.

We have investigated the issue of the field of tolerances for the deviation of the gradients of the lenses from the nominal value. No too severe restrictions on the precision of control over the currents of the lenses were found. In fact, deviations of the field in the lenses and solenoids of up to 10% lead to no substantial increase in the vertical emittance.

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