POLARIZATION ISSUES AND SCHEMES FOR ENERGY CALIBRATION

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Abstract

The paper presents an overview of problems related to production, acceleration and subsequent utilization of the polarized electron and positron beams for the precise energy calibration in the future FCC-ee storage rings. Advantages and disadvantages of the proposed method of free precession spin frequency measurement are discussed.

INTRODUCTION

As truly stated in [1], the polarized beams can be of interest for two reasons: they allow for an accurate energy calibration using resonant depolarization, which will be a crucial advantage for measurements of M_Z, G_Z, and M_W, with expected precisions of order 0.1 MeV; and they are necessary for physics program with longitudinally polarized beams. Taken seriously into consideration the last request we came to the following polarization scenario:

- No use of self-polarization in a collider - too slow with r=11 km: τ=190 hours at Z-peak.
- Polarized electrons acceleration chain started from a Ga-As photo-gun illuminated by a circularly polarized laser light, followed by acceleration to the energy of an intermediate damping ring (1-2 GeV) and then after cooling by SR again acceleration by a linac up to 20 GeV. After then they will be accelerated by a synchrotron up to the top beam energy of a collider (45 – 175 GeV).
- Positrons produced by the conversion of the accelerated to 5-10 GeV electrons are injected into a damping ring. Main part of the cooled via SR-damping positrons will be utilized for the un-polarized collisions. The remaining fraction of positron bunches will spent much longer time, about few minutes, in a special damping ring equipped by the polarization wigglers. These positrons, after became polarized to 10-40% degree, will be accelerated similarly to electrons via the linac and the synchrotron.
- Preservation of the polarization in the booster synchrotron should be guaranted by the installation there of a number of Siberian Snakes.
- The equilibrium spin direction in both collider rings is vertical. But the spin precession frequency could be determined using two methods: by the resonant depolarization technique, see [2-3], and, alternatively, by measuring a free precession Fourier spectrum.
- In the last approach the injected beam polarization vector is perpendicular to the vertical axis.
- The Compton backscattering longitudinal laser polarimeter we propose to use for detection of a coherent spin precession.
- Our estimations reveal a possibility to measure the average beam energy with the accuracy of the order 10^{-6} in single injection shot.

One should keep in mind that resonant depolarization is limited for the use of up to 80-100 GeV per beam. At higher energies the non-polarization methods of the energy monitoring should be considered. Such two possibilities are discussed in [4, 5]. Still calibration by the resonant depolarization shall validate these techniques for the use at higher energies.

POLARIZED BEAM ACCELERATION WITH SIBERIAN SNAKES

When polarized electron beam is accelerated say from 20 GeV to 80 GeV it crosses more than 130 of integer spin resonances spaced by 440.65 MeV. Due to small field errors it will become fully depolarized even by a single cross of such a resonance.

In 70-th Derbenev and Kondratenko have suggested an idea of the Siberian Snake [6]. This is some kind of a spin rotator which rotates spin by 180^0 around any axis which is perpendicular to the vertical one. In a ring with equally spaced odd number of snakes the closed spin orbit looks like it is shown in the Fig.1: everywhere in arcs spins are lying in the medium plane of an accelerator.

Another remarkable fact is that with the odd number of snakes the fractional part of the spin tune always equals to ν=0.5, thus all the spin resonances became eliminated! Still strong enough spin perturbation may destroy the regular spin motion making it non-adiabatic. It may happen, if any k-th harmonic amplitude of a perturbation exceeds or approaches to w_k~0.5.

Other mechanism, which one should take into account, is the radiative depolarization. More details on that are presented in [7]. Here we want announce only the rough depolarization time estimates, achieved analytically and by running the code ASPIRRIN [8]. With 3 snakes in the isomagnetic ring with the bending radius r=11 km τ_p =320 s at E=45 GeV and τ_p =6 s at E=80 GeV.

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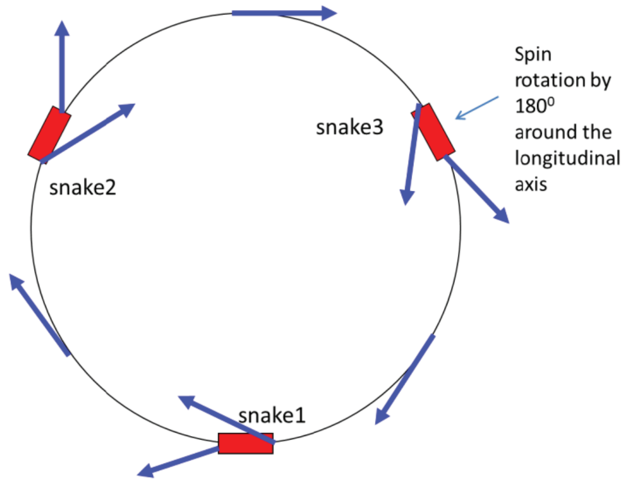

Figure 1: Schematic of spin rotation in a ring by 3 solenoid type snakes.

LONGITUDINAL COMPTON BACKSCATTERING POLARIMETER

Compton backscattering of the circularly polarized laser light on highly relativistic electron exhibits extremely large analysing power to the longitudinal component of an electron polarization. The unpolarised $\sigma_0(a,x)$ and the polarised fraction $\sigma_1(a,x)$ of differential cross-sections be expressed in units πr_e^2 are [9]:

$$\sigma_0(a,x) = \frac{1}{1+a(1-x)} + \frac{1}{[1+a(1-x)]^2} - \frac{1-x^2}{[1+a(1-x)]^3}$$

$$\sigma_1(a,x) = -a\left[1+\frac{1}{1+a(1-x)}\right]\frac{x(1-x)}{[1+a(1-x)]^2}$$

Here $a = 2\gamma\omega_0/m$ is the ratio of the energy of the incident laser photon, taken in the rest system of an electron, to the mass of an electron m and $x = \cos\theta$ is the cosine of the scattering angle in that system.

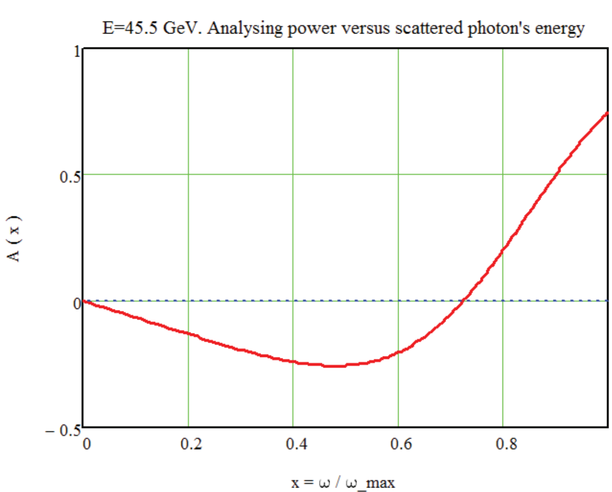

Figure 2: Spectral density of the analysing power of the Compton scattering of the circularly polarized laser light photons with ω_0=2.33 eV on E=45.5 GeV electrons.

The analysing power is defined as the ratio of these two cross-sections $\sigma_1(a,x)/\sigma_0(a,x)$. In the Figure 2 is plotted the dependence of the Compton scattering analysing power versus the energy of the scattered photon. At the edge it reaches the huge value of 75%! For polarization measurements we should rely, of course, on detection of such events. But the counting rate of photons might be so high that events overlap in time. Then, one can rely on a measurement of the average over the full spectrum photon energy asymmetry, as it was done by the HERA team [10]. In the lab system the energy of the scattered photon equals to:

$$\omega_{lab} = \gamma m \frac{a(1-x)}{1+a(1-x)} .$$

The edge of the photon spectrum corresponds to the backscattering case: $x = -1$. As example, at E=45.5 GeV and with ω_0=2.33 eV one gets a=0.812, ω_{lab}=28 GeV. Dramatically large energy loss by the electron, comparable with its initial energy!

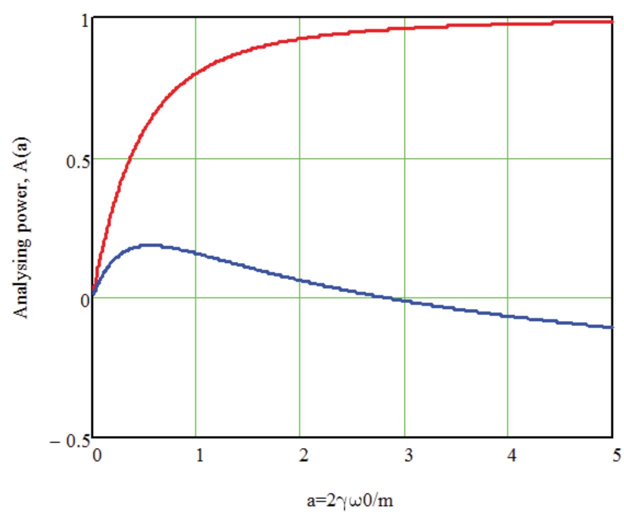

Figure 3: Averaged (blue) and maximal (red) spectral analysing powers of the Compton scattering of the circularly polarized laser light photons with energy ω_0=2.33 eV by 45.5 GeV electrons.

The integrated over x (in other words over a solid angle) total cross-sections are:

$$\sigma_0(a) = \frac{\ln(1+2a)}{a} - \frac{2(1+a)\ln(1+2a)}{a^3} + \frac{4}{a^2} + \frac{2(1+a)}{(1+2a)^2} .$$

$$\sigma_1(a) = \frac{2\left(1+4a+5a^2\right)}{a(1+2a)^2} - \frac{(1+a)\ln(1+2a)}{a^2}$$

Omitting the factor γm from the expression for ω_{lab} and integrating its product with $\sigma_{0,1}(a,x)$ over x we come to unpolarised and polarized contributions to average over the spectrum photon energy:

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$$E_0(a) = \frac{2(9 + a(51 + a(93 + a(51 - 10a))))}{3a^2(1 + 2a)^3} - \frac{(1 + a)(3 - a)\ln(1 + 2a)}{a^3}$$

$$E_1(a) = \frac{2(6 + a(33 + a(59 + 38a)))}{3a(1 + 2a)^3} - \frac{(2 + a)\ln(1 + 2a)}{a^2}$$

The ratio $E_1(a)/E_0(a)$, shown by blue line in the Figure 3, describes the averaged over the spectrum analysing power dependence on the parameter a, while the red curve shows such dependence of the on edge spectral analysing power. Still, average photon energy asymmetry does not exceed 18.5% and even changes a sign for $a > 2.8$.

We suggest detect not photons but lost momentum electrons, which are magnetically well separated according to their energies and do not overlap with softer electrons. Then events, belonging to the spectrum edge of the Compton scattering, could easily be selected.

FREE SPIN PRECESSION DATA ANALYSIS

Polarization vector of the injected into collider beam could be directed horizontally. This is just the case for the synchrotron with 3 Siberian Snakes: there spins are horizontal everywhere. After injection spin assembly starts free precession around the vertical axis and using the described above a longitudinal laser polarimeter one can measure the fractional part of the spin tune. The first question raised is: how long such free precession may last.

To answer to this question the author has performed a simple the synchrotron and spin motions turn by turn tracking. Parameters of a ring model where taken just that are tabulated to FCC-ee 80 GeV regime. Namely, the synchrotron energy spread δ was set to $\sigma_\delta=8\cdot10^{-4}$ and the damping time was taken $\tau_\delta=243$ turns. Random energy jumps, being normally distributed, and the radiative damping were applied every turn. Linear and the second order spin tune chromaticity also were included into the game. The last one was taken $\Delta\nu=\nu_0\cdot\delta^2$ with $\nu_0=181.27$. Results are presented in the Figures 4-6.

Remark: without the quadratic on energy deviation spin tune dependence the de-phasing of a spin assembly do not develop just after one damping time. The Figure 5 shows how such spread of spin angles develops in time.

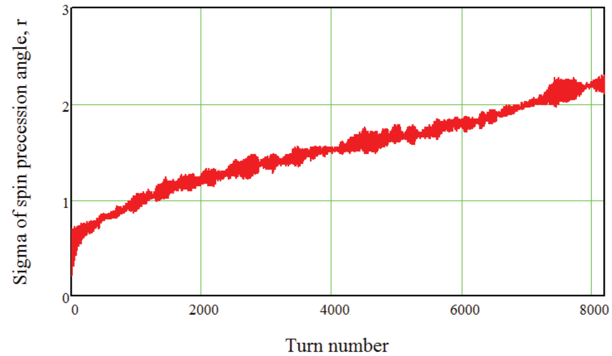

Figure 4: Increase of the spin precession angles spread with the time due to energy spread in a beam in average. The synchrotron amplitudes energy spread is $8\cdot10^{-4}$ and the energy spread in average is postulated be $6.4\cdot10^{-7}$.

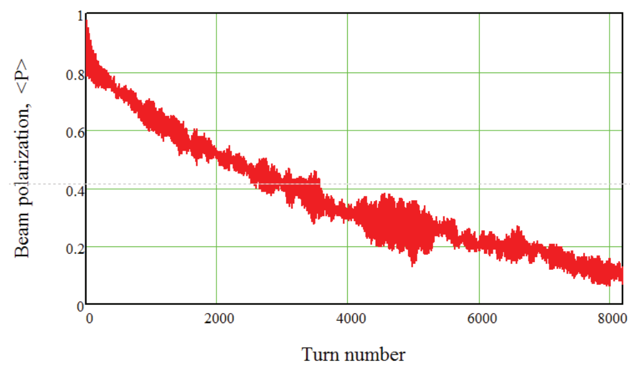

Figure 5: Beam polarization decay due to de-coherence of the spin precession, caused by the dependence of a spin tune on square of the energy deviation, $\Delta\nu=\nu_0\cdot\delta^2$.

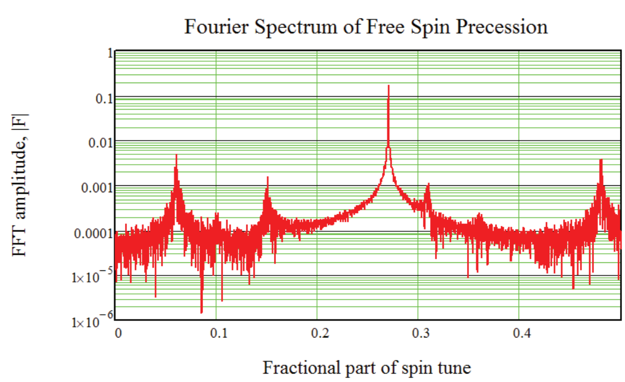

Figure 6: Fourier spectrum of the free spin precession of 250 particles. A spectrum was accumulated in 8192 turns.

Finally a nice Fourier spectrum, accumulated during 8192 turns, is presented in the Figure 6. The first, second and the third order synchrotron side bands are visible ($\nu_s=0.21$) there. The position of the central peak is shifted from a reference particle's value $\Delta\nu_0=0.27$ by the amount $\Delta\nu=0.00023$. This corresponds to about $\Delta E=100$ keV deviation of the energy from the reference value, but the statistical sigma of the energy determination is much smaller.

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CONCLUSION

The discussed above approach, based on idea to measure the free precession spin frequency looks promising for application at super-high electron-positron storage rings, like FCC-ee. The longitudinal Compton polarimeter can provide very fast and extremely reliable data for the Fourier analysis.

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