Accelerating and injecting polarized beams into FCC-ee

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FCC-week, Berlin, 01 June 2017

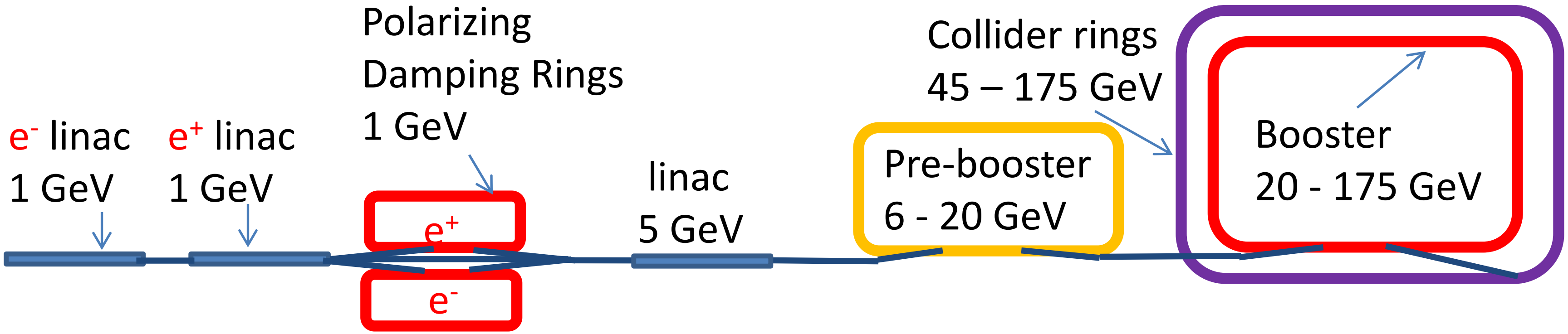
Outline

- Introduction to a concept.
- Polarizing damping rings.
- Acceleration of polarized beams in the booster synchrotrons.
- Evaluation of the depolarization rates.
- Free spin precession approach proposed for fast determination of the average beam energy.
- Conclusion.

Introduction

- FCC-ee demands 50 keV beam energy resolution at Z and 100 keV at W, separately in e^+ and e^- rings.
- Only the resonant depolarization (RD) can provide such extreme absolute accuracy: $\Delta E/E < 1 \cdot 10^{-6}$!
- Two 1 - 1.5 GeV damping rings with high field bends can provide fast self-polarization of both beams.
- Every 10-20 s one or few polarized bunches will be extracted from the damping ring and will be accelerated in a 5-6 GeV linac and then in the cascade of synchrotrons (6-20, 20-45… 175 GeV).
- Preservation of the polarization will be provided by the use of the solenoid type spin rotators (Siberian Snakes) installed in 2 or 4 straight sections of each synchrotron.

Acceleration scheme for FCC-ee: options #1, #2



e^- linac
1 GeV

e^+ linac
1 GeV

Polarizing
Damping Rings
1 GeV

e^+

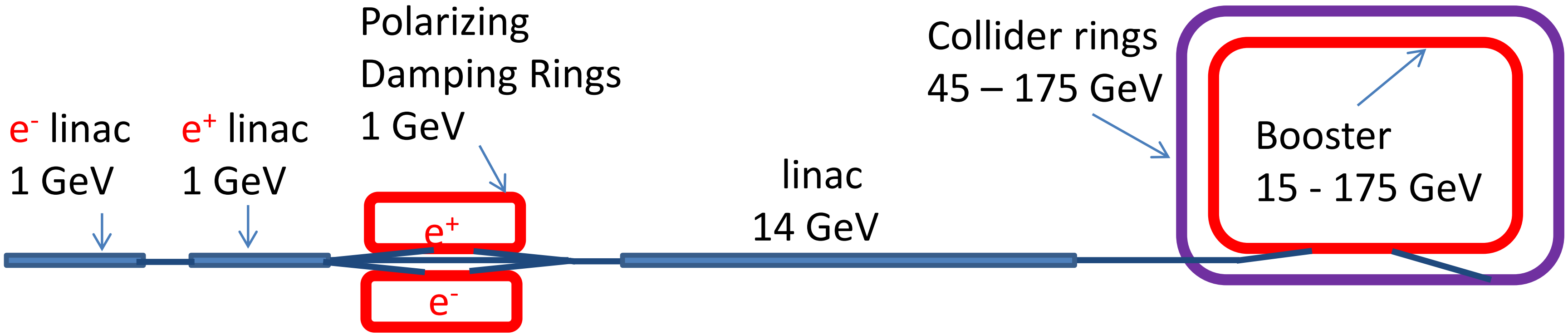
e^-

linac
5 GeV

Pre-booster
6 - 20 GeV

Collider rings
45 – 175 GeV

Booster
20 - 175 GeV



e^- linac
1 GeV

e^+ linac
1 GeV

Polarizing
Damping Rings
1 GeV

e^+

e^-

linac
14 GeV

Collider rings
45 – 175 GeV

Booster
15 - 175 GeV

Pro and contra of two acceleration scheme options

- No degradation of the polarization in a linac is expected.
- Repetition frequency of a linac is high.
- But synchrotrons are cheaper compared to linacs!?
- Still the use of many fast ramping solenoids in spin rotators presents a certain challenge:
    1) Heat released in coils due to eddy currents – a first problem.
    2) High ramp voltage dictates use of many solenoid sections, powered by the independent power-converters.
- So, it is preferable to eliminate extra synchrotrons except of the last one, which will share a tunnel with the collider and will be not too fast ramping (~10 seconds).

Polarizing damping ring optimization

- Optimal energy is about 1 GeV. It is large enough to suppress IBS and small enough not radiate too much SR power.

$$\left.\begin{aligned}\tau_{ST}{}^{-1} &\square\ B^3E^2\frac{\rho}{R}\\ \left\langle \dot{E}\right\rangle &\square\ B^2E^2\frac{\rho}{R}\end{aligned}\right\}\quad\rightarrow\qquad \Delta E_{\text{Polarization}}=\left\langle \dot{E}\right\rangle \tau_{ST}\ \square\ \frac{1}{B}$$

- SLAC was operating very successfully 1.2 GeV damping rings!
- From polarization point of view it is preferable to use the high field bends instead of asymmetric field wigglers. Currently we propose to use of B=5.5 T short dipole magnets (24 identical dipoles, 15^0 each).
- But SC wigglers are better developed, could also be considered as an option.

Polarizing ring parameters

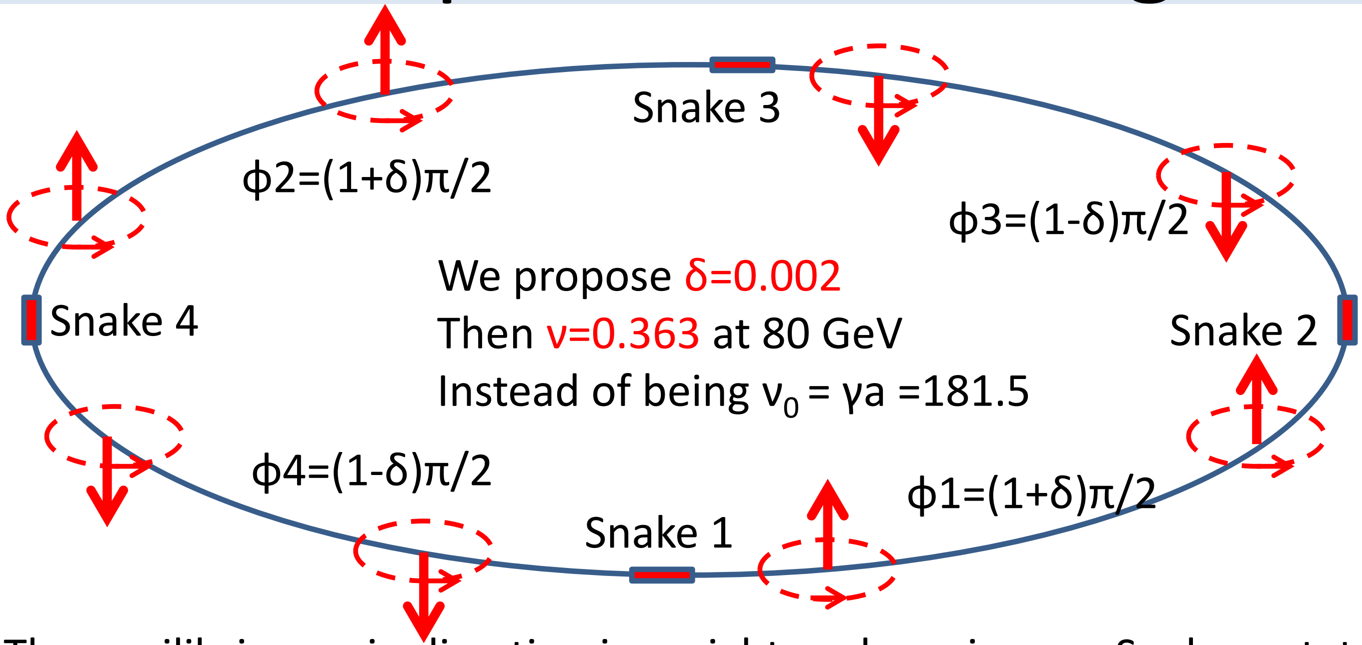
Energy, E	1	GeV
Circumference, C	22	m
Average radius, R	3.5	m
Bending radius, ρ	0.6	m
Bending field, B	5.5	T
Energy loss / turn, U_0	145	keV
Momentum spread, σ_p	0.00155	
Number of e± per bunch, N	10^{10}	
Number of bunches, N_b	16	
Total beam current, I	350	mA
SR powrer	50	kW
Sokolov-Ternov polarization time , τ_{ST}	127	s
Polarization degree	70	%
Injection/Ejection time periodicity, T_0	10	s

Here we assume that every bunch spends in a ring $T_0 \cdot N_{b=}$=160 s before extraction.
So, the polarization degree is high enough, in the order of 70%!
Every 10 s one bunch is assumed to be extracted for the energy calibration purposes .
Use of high bending field is energetically beneficial to obtain the required polarization degree.

High energy booster synchrotron demands

- Fast acceleration from 15-20 GeV up to 175 GeV of train of unpolarized e± bunches to keep the collider luminosity constant within 10% or better.
- Preserve during acceleration the polarization of one or few polarized bunches, which are extracted from the polarizing damping ring and be added to the train of unpolarized bunches.
- The Resonant Depolarization technique can work only below 80-100 GeV (extrapolation from LEP studies). So, there is no much sense to build spin rotators for operation at higher energy.
- Energy measurement above 80-100 GeV shall be provided by the magnetic spectrometers, which will be calibrated by RD below that threshold.

Closed spin orbit in a ring with 4 snakes

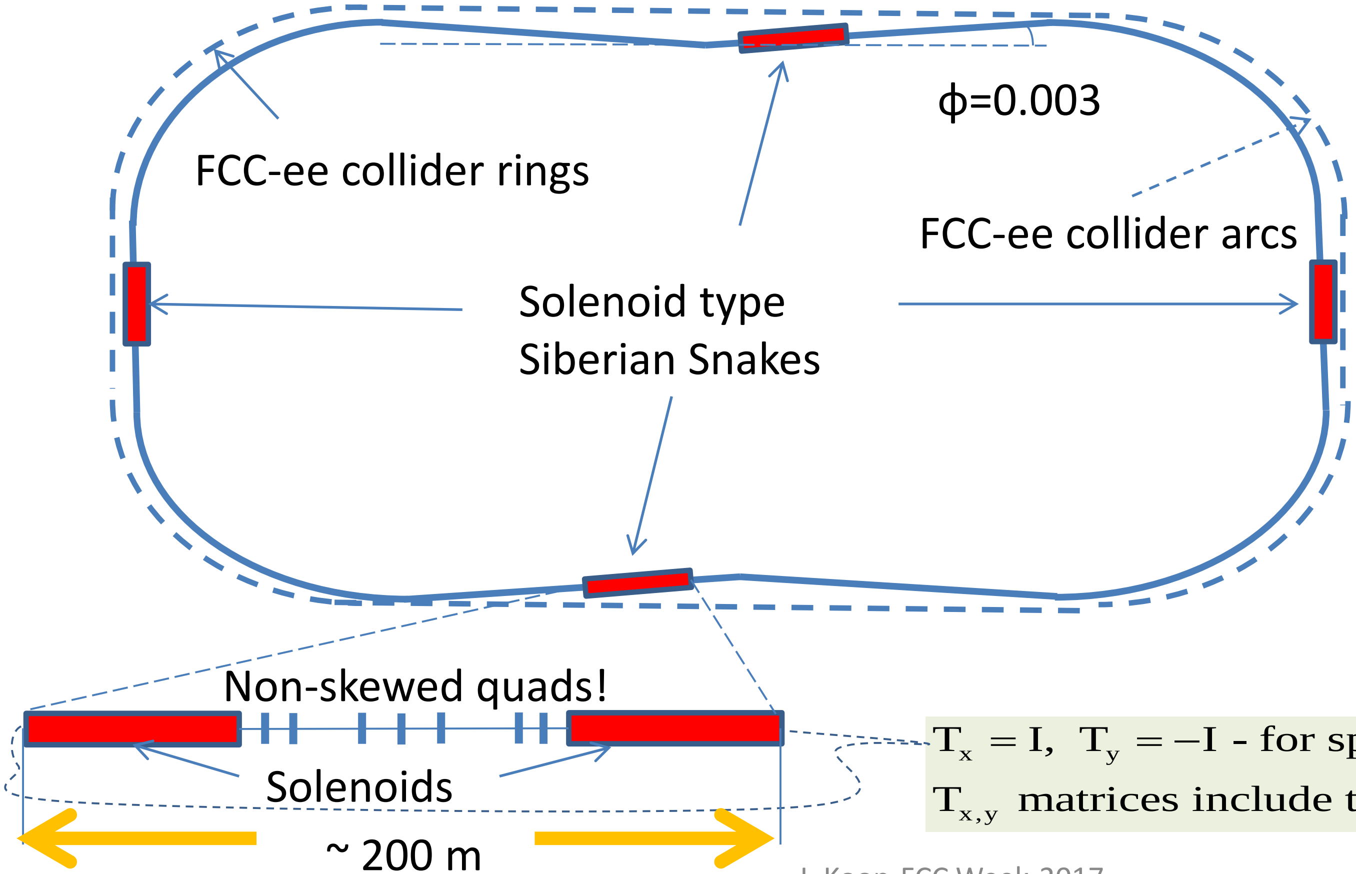


We propose $\delta=0.002$
Then $\nu=0.363$ at 80 GeV
Instead of being $\nu_0 = \gamma a = 181.5$

In 70-th such approach was considered by A.Kondratenko, for FCC-ee discussed by S.R. Mane: arXiv:1406.0561v1, physics.acc-ph 3 Jun 2014.

The equilibrium spin direction is upright or down in arcs. Snakes rotate spin by 180^0 around the longitudinal direction. The spin precession frequency will be zero in case of equally spaced snakes. To make the spin motion stable , a small asymmetry of “positive” and “negative“ arcs has to be foreseen: $\phi=(1\pm\delta)\pi/2$. Then the spin tune became reduced to $\nu= \delta \cdot\nu_0$. Here $\nu_0=\gamma a$ is the unperturbed spin tune, with the anomalous magnetic moment: $a=0.00115965218$7….

Booster ring for FCC-ee top up injection



FCC-ee collider rings

$\phi=0.003$

FCC-ee collider arcs

Solenoid type
Siberian Snakes

Non-skewed quads!

Solenoids

~ 200 m

Four snakes spaced by the azimuthal angle $\pi/2 \pm \phi$ from each other will reduce the spin precession tune by the factor $2\phi/\pi$.

With $\phi=0.003$, one gets $\nu=0.36$ at $E=80$ GeV, instead of being $\nu_0=181.5$ w/o snakes.

$T_x = I,\ T_y = -I$ - for spin transparency! Remind:
$T_{x,y}$ matrices include the solenoids edges as well!

Depolarization in presence of snakes

Derbenev-Kondratenko formula:

$$\tau_p^{-1} = \frac{5\sqrt{3}}{8}\lambda_e r_e c\gamma^5 \left\langle \left|K^3\right| \left(1 - \frac{2}{9}(\vec{n}\vec{v})^2 + \frac{11}{18}\vec{d}^2\right)\right\rangle \approx \tau_{ST}^{-1}\frac{11}{18}\left\langle \vec{d}^2 \right\rangle$$

$K = \rho^{-1}$, $\left|\vec{v}\right| = 1,$ $\vec{d} \equiv \gamma\left(\partial\vec{n}/\partial\gamma\right)$ - spin-orbit coupling vector

Spin transparency cancels the betatron contribution: $\vec{d} = \vec{d}_\gamma + \cancel{\vec{d}_\beta}$

For m pairs of snakes $\left\langle \vec{d}^2 \right\rangle \square\ \nu_0^{\ 2} w^2/m^2$, Here $\nu_0 = \gamma a,$

w - spin perturbation (due to orbit distortions, or other field errors)

Tracking simulations, ASPIRRIN code, analytic results, all give:

For E=80 GeV , m=2, w=0.1 we find $\left\langle \vec{d}^2 \right\rangle \square\ 4000 \quad \to \quad \tau_d \approx 18$ s

This ensures small polarization loss, if $t_{ramp} \le 12$ s. OK!

Tolerances on the orbit distortions

Tolerances on the vertical orbit distortion y(s):

Spin rotation angle kick produced by a single quad: $\varphi_1 = \nu_0 \cdot \Delta y_1'$

Number of quads in a ring: $N \Box 2500$

Statistically indepent N kicks will produce the total spin rotation:

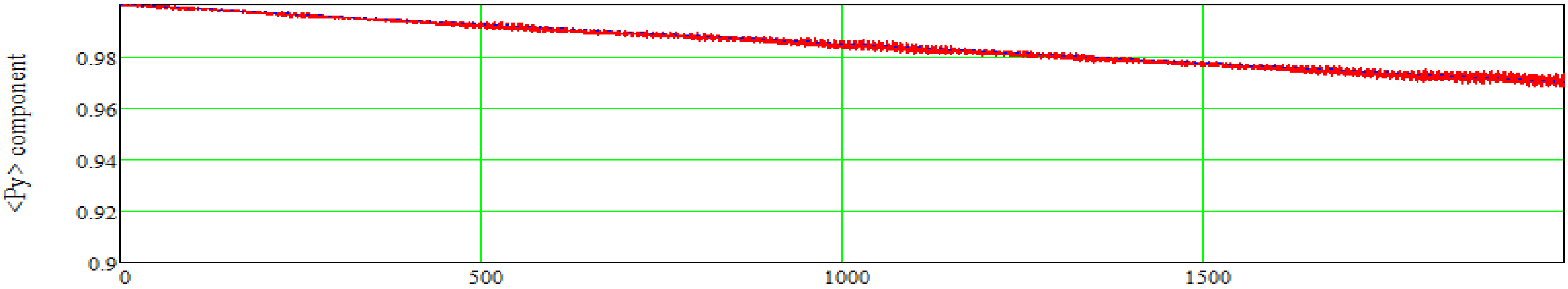
$\varphi_\Sigma \Box \nu_0 \cdot \Delta y_1' \cdot \sqrt{N}$ Now we want: $\varphi_\Sigma \le w \cdot 2\pi,$

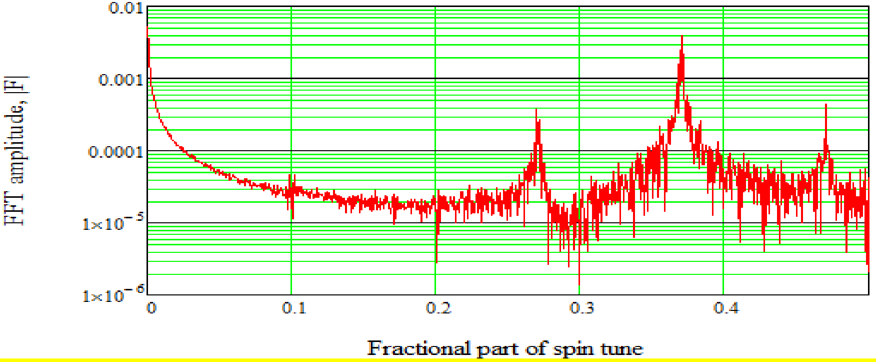
Here w - single equivalent by strengh the spin perturbation tune

Spin tracking shows that w=0.1 is tolerable for booster at 80 GeV

Thus we get: $\Delta y_1' \le \dfrac{w \cdot 2\pi}{\nu_0 \cdot \sqrt{N}} \Box 6 \cdot 10^{-5} \quad \rightarrow \quad y_{rms} \Box \Delta y_1' \cdot \beta_y \Box 6\ \mathrm{mm}$

Spin tracking of the depolarization process


Radiative depolarization: 4 snakes, 80 GeV, σ_E=0.00065, λ=1/240, ν=0.363, perturbation w=0.1



Spin tracking of 1000 particles in a ring with the spin perturbation w=0.1.
The depolarization time 18 s is sufficient for acceleration to 80 GeV in 10 s.
Due to perturbation the spin precession frequency became shifted to 0.3702 from the ideal 0.3631 value.

Spectrum of the transversal polarization component.
Side bands are spaced by synchrotron tune ν_s=0.1

How to utilize polarized bunches in FCC-ee

The accelerated to Z or W thresholds polarized bunches can be used for energy calibration in FCC-ee in two ways:

1) They simply can be resonantly depolarized, being injected into collider with vertical direction of spin.

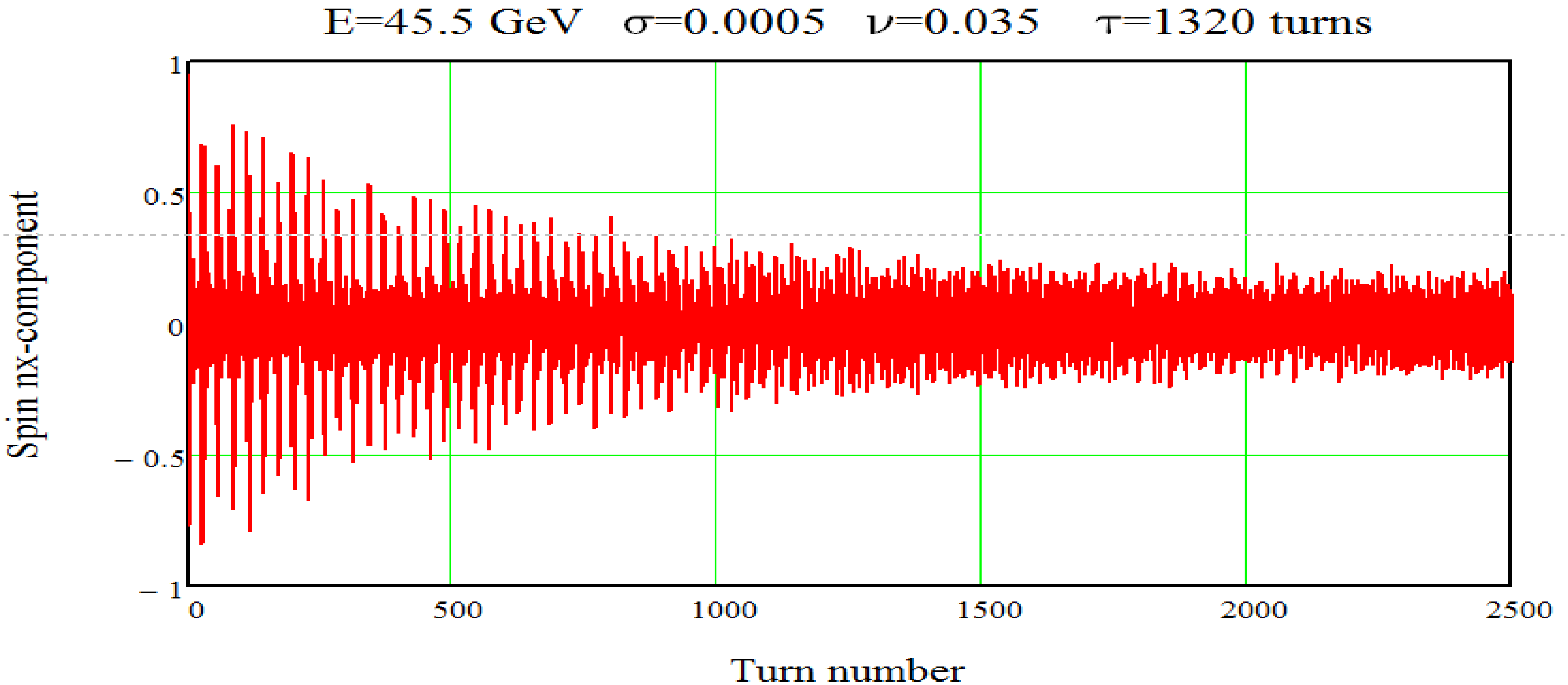
2) Alternatively, they can be injected with spins directed in the horizontal plane. And using the laser polarimeter one can observe the modulation of Compton backscattering cross-section by the coherent precession of bunch spins ensemble.

The last option can provide much faster and robust method of the spin precession frequency determination. Still it works if the synchrotron tune is large enough, only!

Few examples of spin tracking results are presented in next slides.

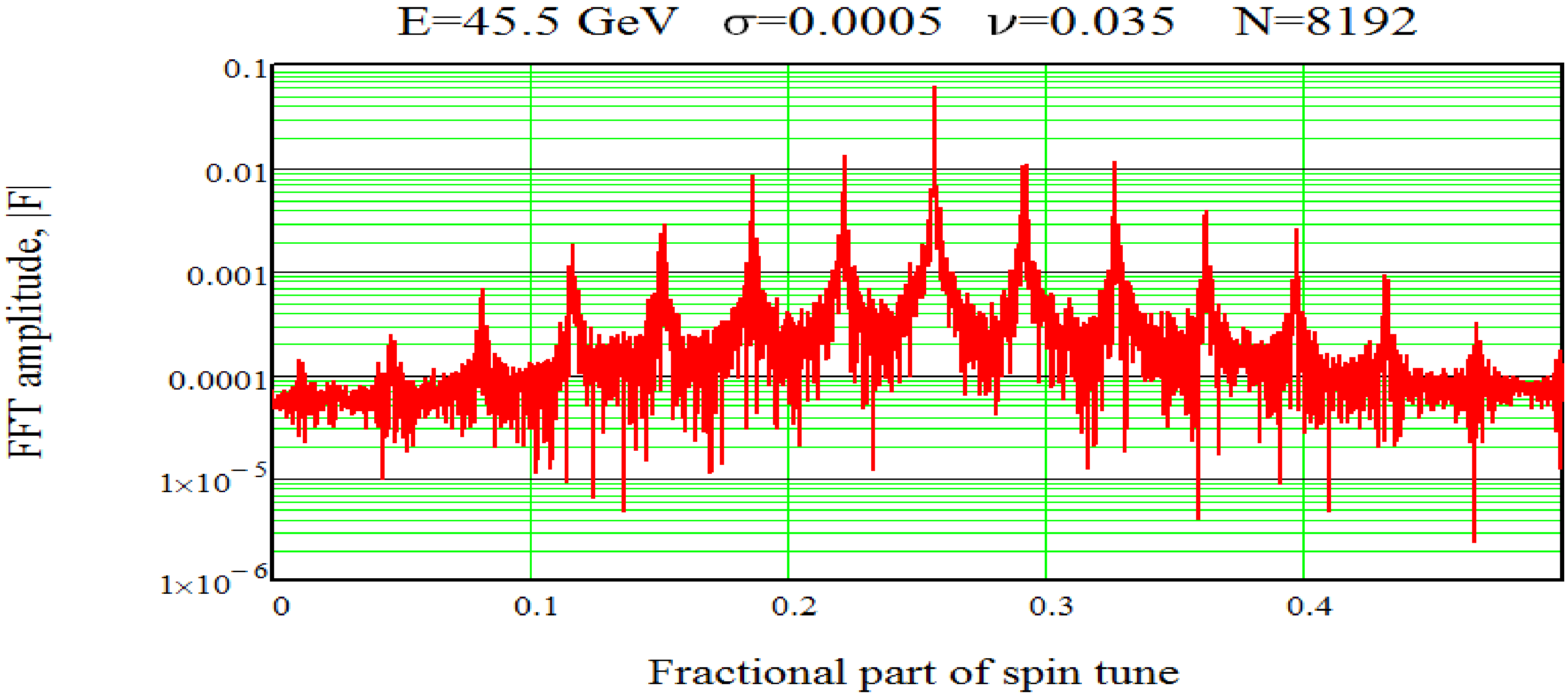
Spin tracking oscillogram. 125 test-particles.

E=45.5 GeV, σ_δ=0.0005, ν_s =0.035, τ_s =1320 turns



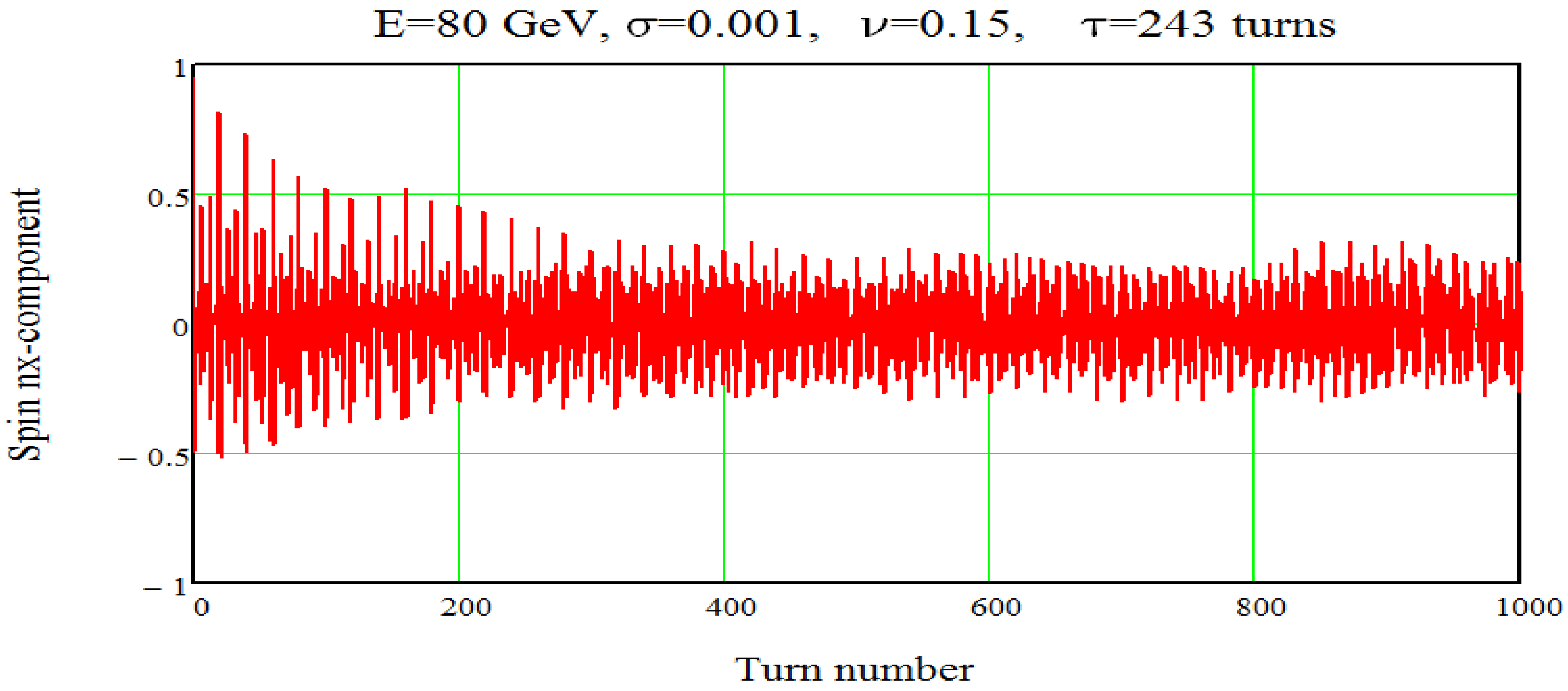
Spin precession spectrum. Number of turns 8192.

E=45.5 GeV, ν_0=103.25, σ_δ=0.0005, ν_s =0.035, χ=1.48

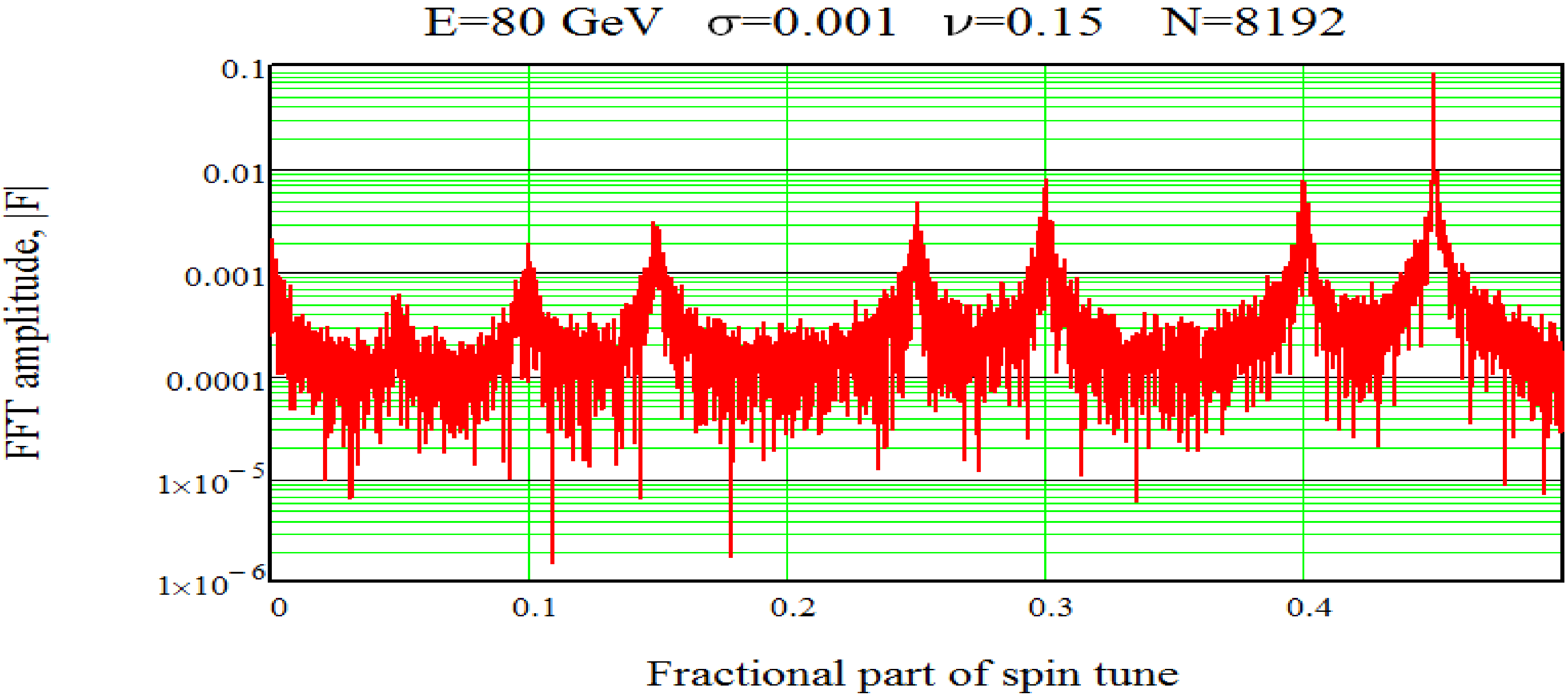


We want: $\chi < 1.7$. With $\chi > 1.7$ peaks in spectrum disappear!

Spin tracking oscillogram. 125 test-particles.
E=80 GeV, σ_δ=0.001, ν_s =0.15, τ_s =243 turns

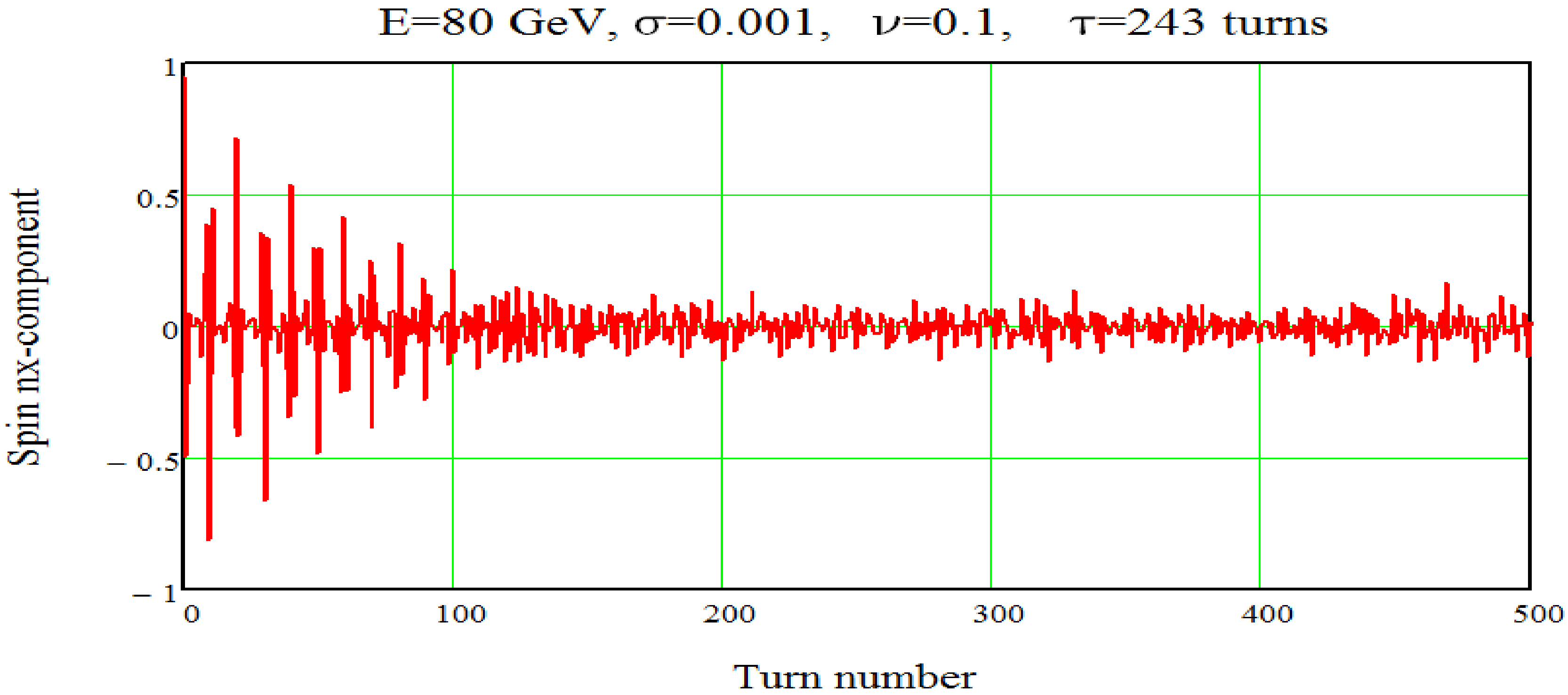


Spin precession spectrum. Number of turns 8192. E=80 GeV, ν_0=181.55, σ_δ=0.001, ν_s =0.15, χ=1.21



Spin tracking oscillogram. 125 test-particles.

E=80 GeV, σ_δ=0.001, ν_s =0.10, τ_s =243 turns



Fast de-phasing due to too slow synchrotron motion!

Conclusion

- Four Siberian snakes installed in the main booster at proper locations provide preservation of the polarization during acceleration up to E=80 – 100 GeV beam energy.
- Free precession approach can be applied for fast determination of the spin tune after injection of single polarized bunch into the collider.
- Important: the synchrotron modulation index should be small: $\chi < 1.8$ $(\chi = \nu_0 \sigma_\delta / \nu_s)$, otherwise it will happen fast decoherence of the spin precession. This leds to operation of the collider with high value of the synchrotron tune: $\nu_s > 0.10$ at E=80 GeV.
- The Sokolov-Ternov self-polarization mechanism requires also small value of the synchrotron modulation index: $\chi < 1$. Seems, unrealistic above 80 GeV?
- A set of energy monitors (well controlled magnetic spectrometers?) shall be used for the local beam energy measurements in the full energy range of FCC-ee.