Accelerating and Injecting Polarized Beams in FCC-ee

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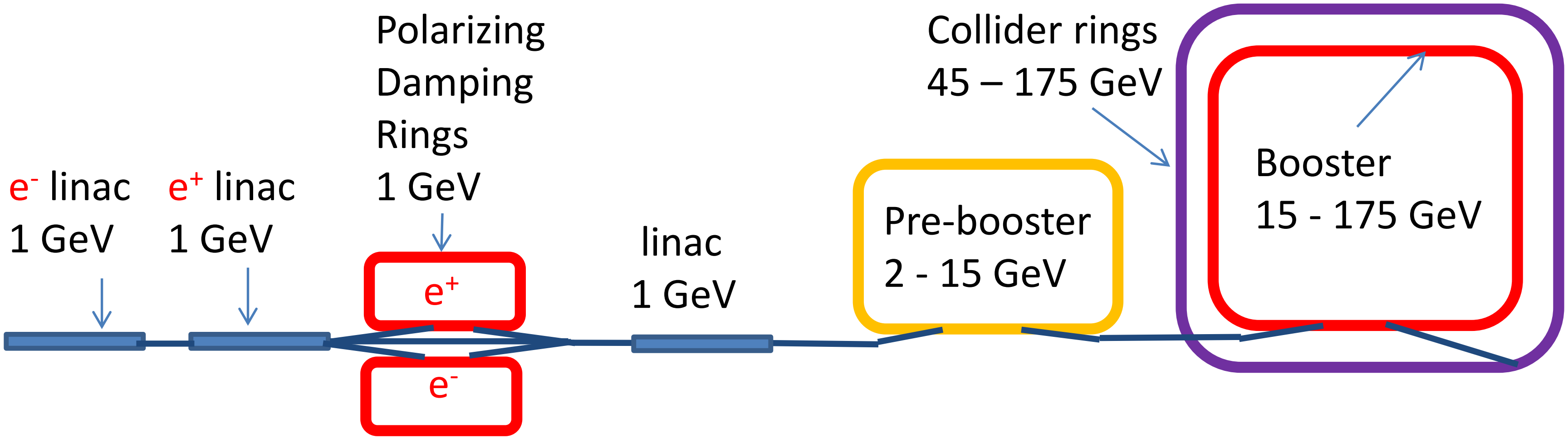
Outline

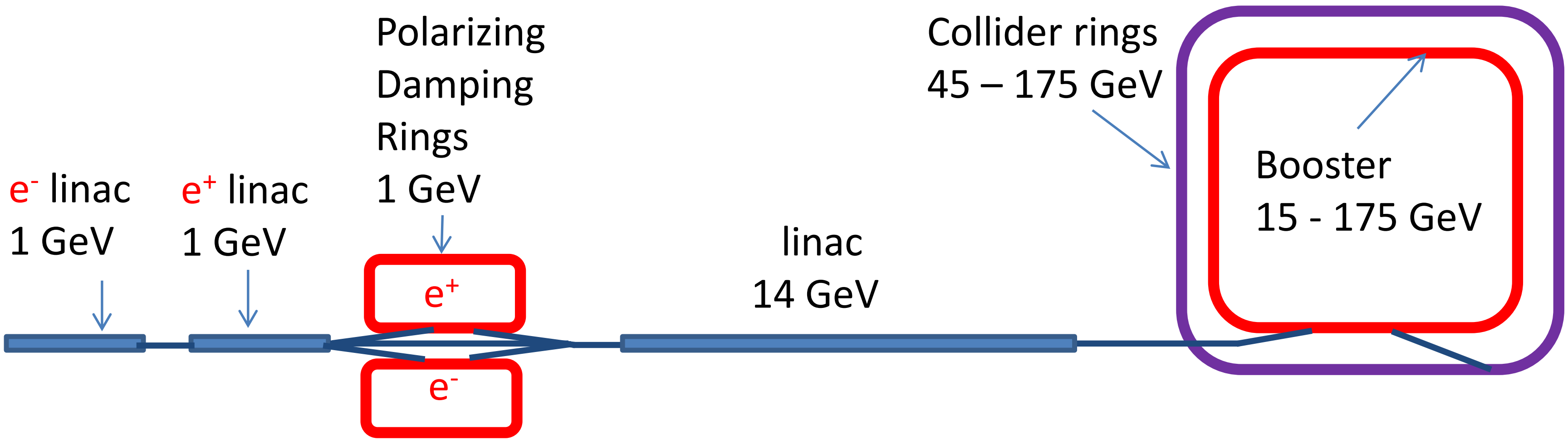
- Introduction.
- A concept.
- Polarizing damping rings.
- Acceleration of polarized beams in a booster synchrotrons.
- Evaluation of the depolarization rates.
- Control of polarization by the longitudinal Compton backscattering polarimeter.
- Conclusion.

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: $\Delta E/E \sim 1 \cdot 10^{-6}$!
- Two independent 1 GeV damping rings with high field bends or wigglers will 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 cascade of synchrotrons.
- 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 every synchrotron.

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





Pro and contra of two acceleration scheme options

- No degradation of the polarization in a linac is expected.
- Repetition frequency of a linac operation is high! Very good!
- 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 not be too fast ramping (~10 seconds).

Polarizing damping ring optimization

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

$$\left.\begin{array}{l} \tau_{ST}^{-1} \propto B^3 E^2 \dfrac{\rho}{R} \\ \left\langle \dot{E} \right\rangle \propto B^2 E^2 \dfrac{\rho}{R} \end{array}\right\} \rightarrow \quad \Delta E_{Polarization} = \left\langle \dot{E} \right\rangle \tau_{ST} \propto \frac{1}{B}$$

- SLAC was operating successfully 1.2 GeV damping ring for years!

- From polarization point of view it is preferable to use the high field bends instead of asymmetric field wigglers. Currently we rely on use of B=5.5 T identical short dipole magnets (about 15^0each) .

- But SC wigglers are better developed. Could also be an option!

Proposed 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
Polarization time (Sokolov-Ternov), 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 only.

Use of high bending field is energetically beneficial to obtain certain polarization degree.

High energy booster synchrotron demands

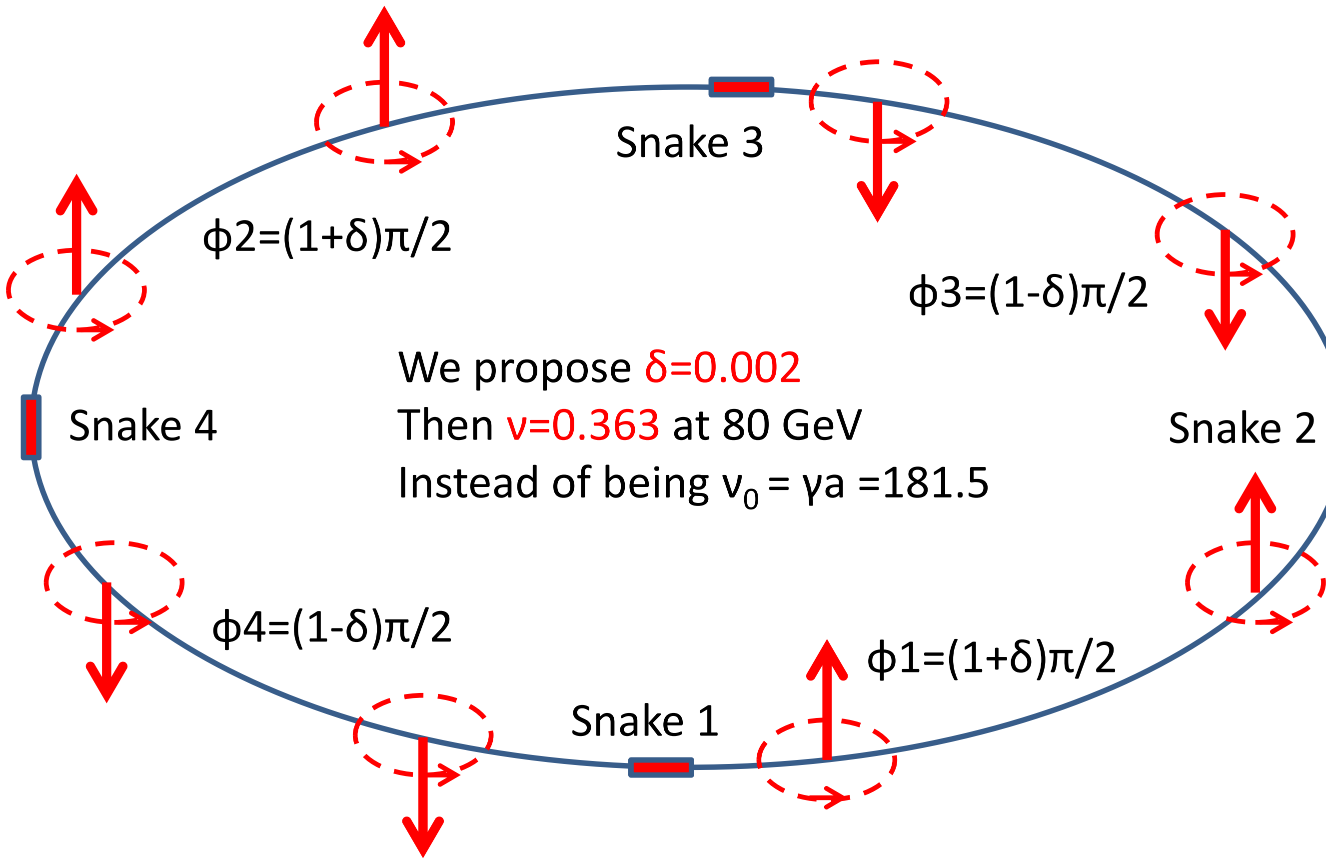
- Fast acceleration from 15 GeV up to 175 GeV train of unpolarized e± bunches to keep the collider luminosity constant within ±5% or better.

- 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 studied and calibrated by RD below that threshold.

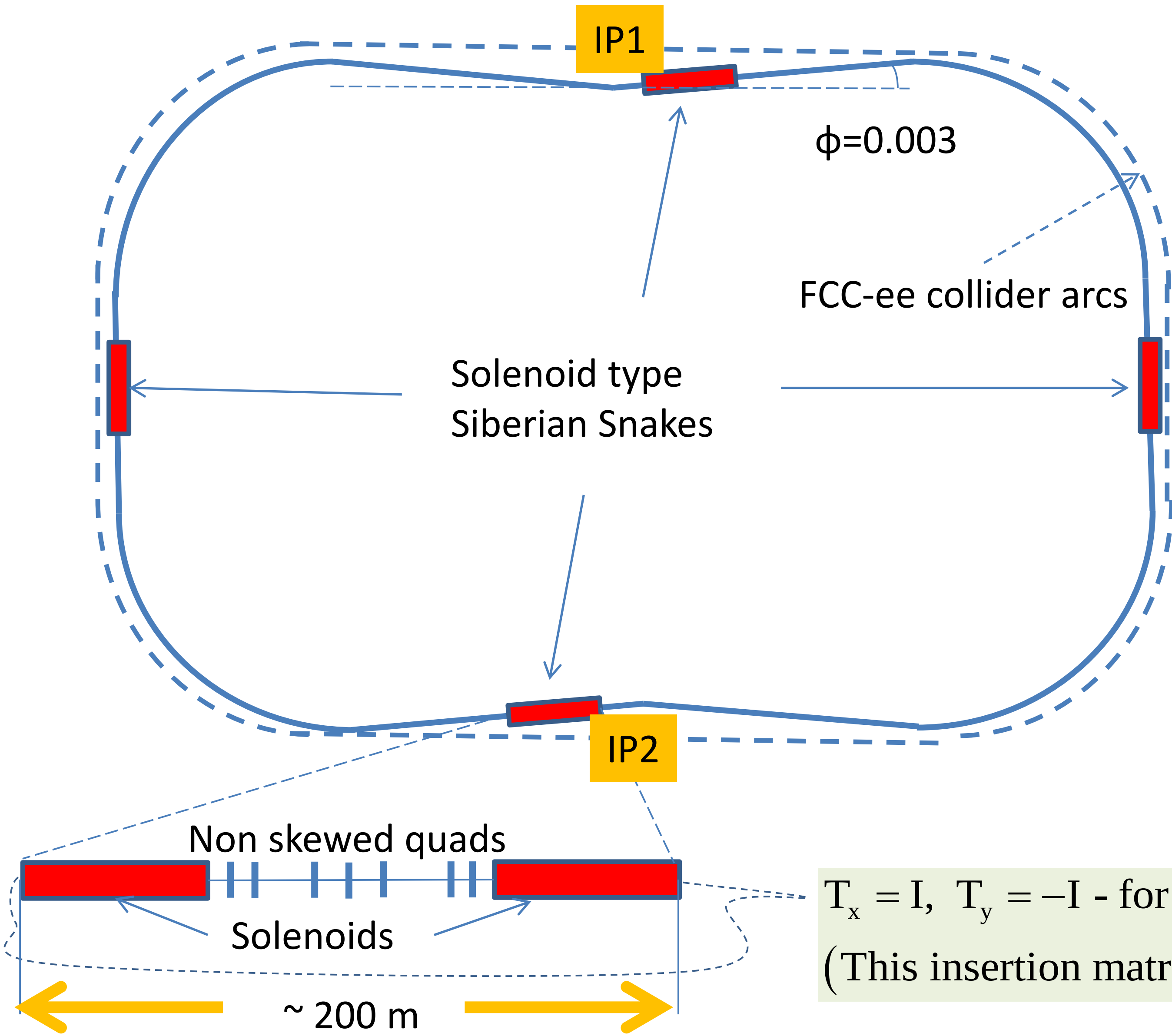
Closed spin orbit in a ring with 4 snakes



In 70-th such approach was considered by A.Kondratenko, for FCC discussed by S.R. Mane In 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 $\nu_0=\gamma a$ – unperturbed spin tune, with a=0.001159652187… - the anomalous magnetic moment.

Booster ring for FCC-ee top up injection



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

With $\phi=0.003$
$\nu=0.36$ at $E=80$ GeV
instead of be $\nu_0=181.5$
without snakes

$T_x = I,\ T_y = -I$ - for the spin transparency!

(This insertion matrix includes solenoid edges!)

Depolarization in presence of snakes

Derbenev-Kondratenko formula:

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

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

Spin transparency cancels the betatron contribution: $\vec{d} = \vec{d}_\gamma + \not{\vec{d}}_\beta$

For m pairs of snakes $\left\langle \vec{d}^2 \right\rangle \sim \nu_0^2 w^2/m^2$, 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 $\left\langle \vec{d}^2 \right\rangle \sim 4000 \quad \rightarrow \quad \tau_d \approx 18\ \mathrm{s}$

That ensures small polarization loss if $t_{ramp} \leq 12$ s

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: $N \approx 2500$

Statistically indepent N kicks will produce the total spin rotation:

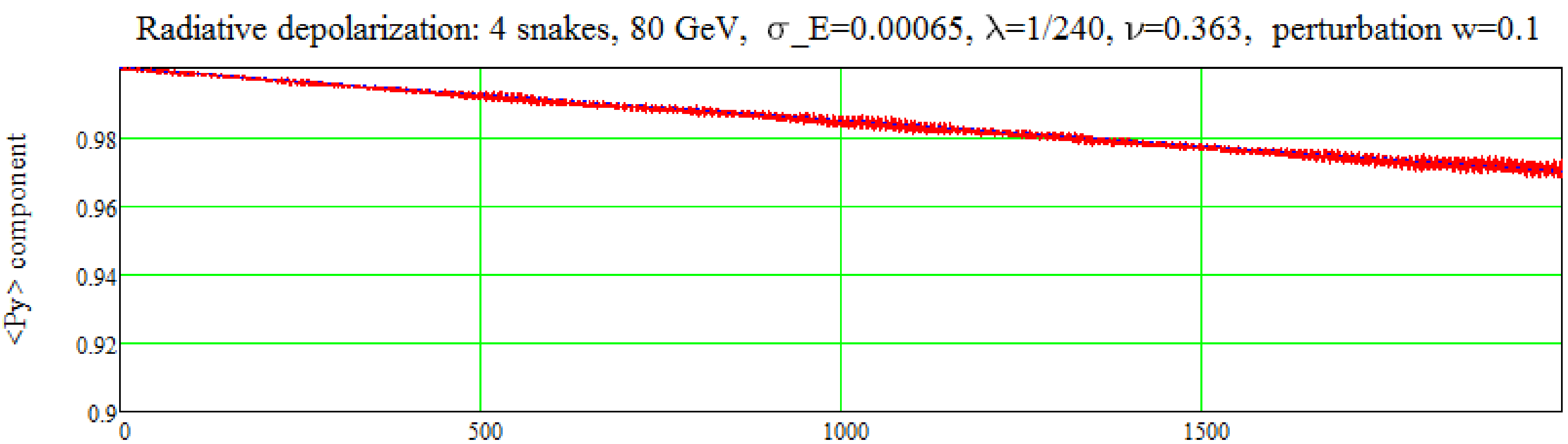
$\varphi_\Sigma \approx \nu_0 \cdot \Delta y_1^{'} \cdot \sqrt{N}$ Now we want: $\varphi_\Sigma \le w \cdot 2\pi,$

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: $\Delta y_1^{'} \le \dfrac{w \cdot 2\pi}{\nu_0 \cdot \sqrt{N}} \approx 6 \cdot 10^{-5} \quad \rightarrow \quad y_{rms} \approx \Delta y_1^{'} \cdot \beta_y \approx 6\,\text{mm}$

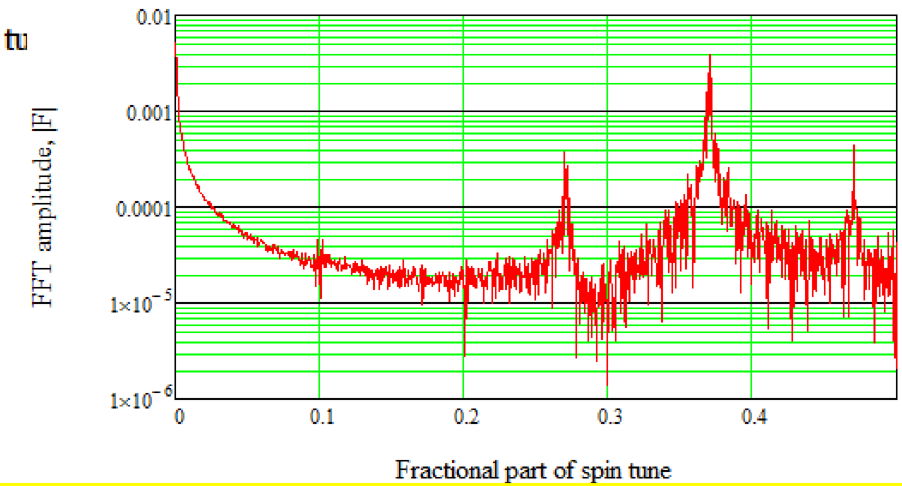
Spin tracking of the depolarization process



Spin tracking of 1000 particles, over 2000 turns in a ring with the spin perturbation w=0.1.

The observed depolarization time 18 s is large enough for acceleration of a beam from 15 GeV to 80 GeV in 10 s.

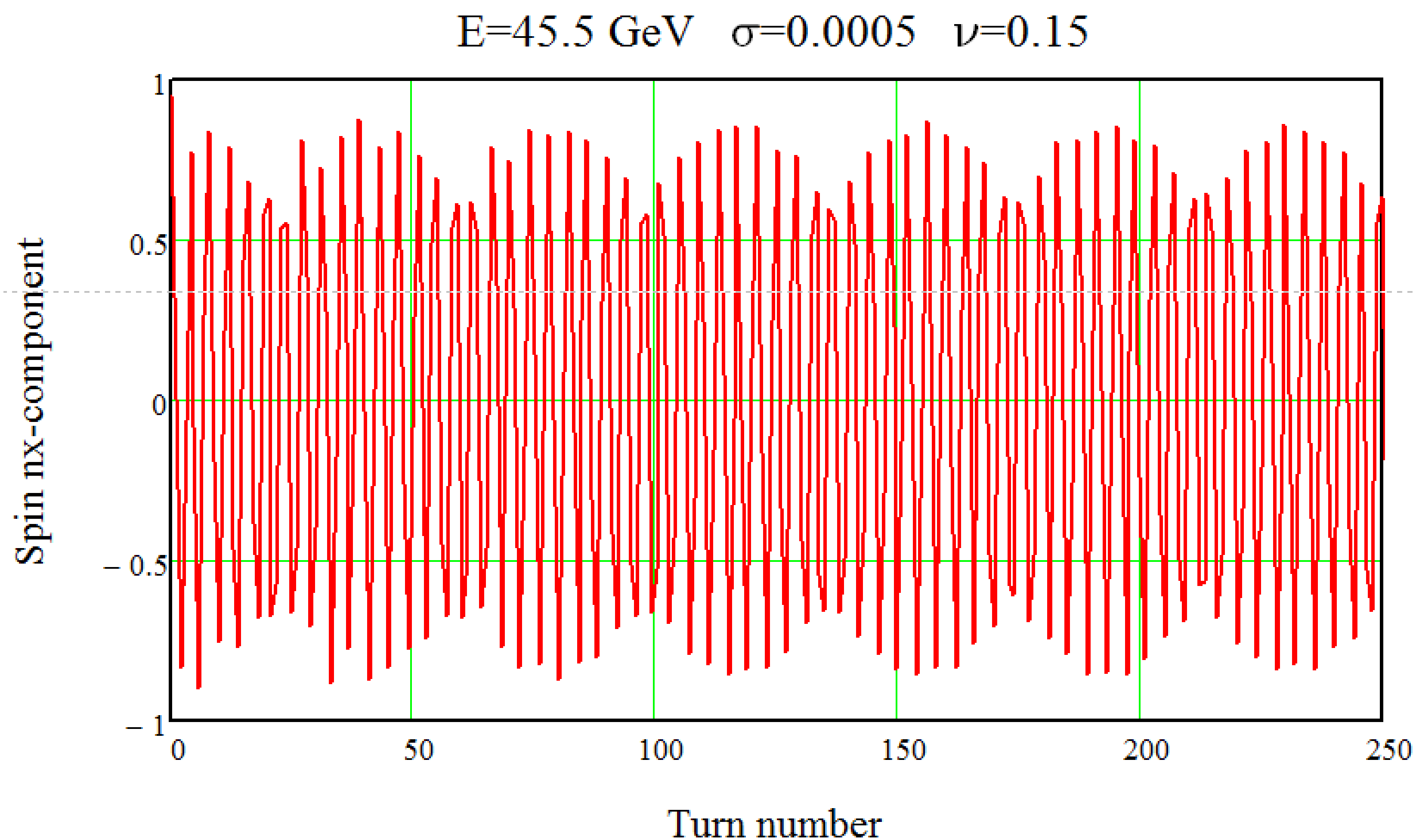
Due to perturbation (w=0.1) the spin precession frequency became shifted to 0.3702 from the ideal 0.3631 value.



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

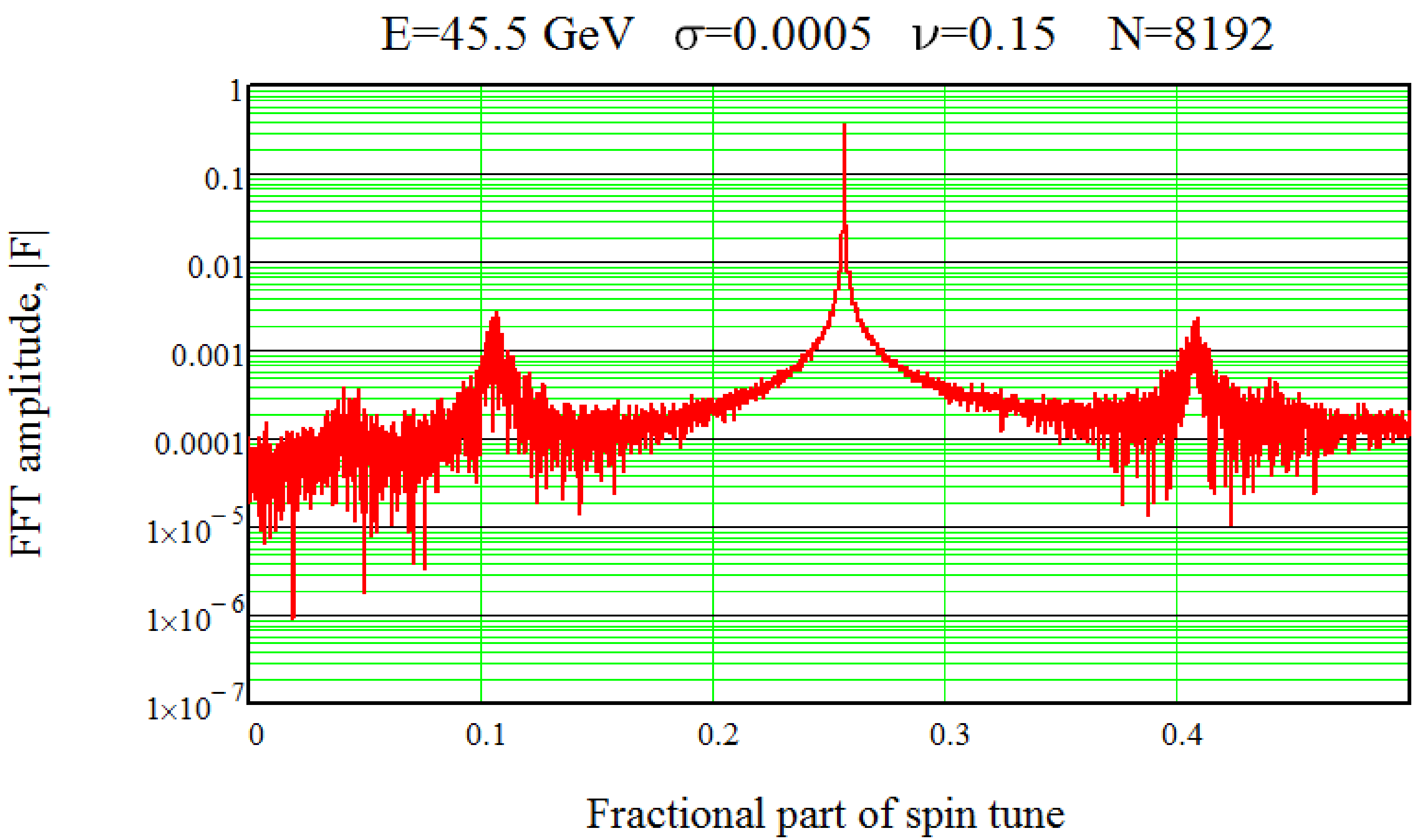
Spin tracking oscillogram. 125 test-particles.

E=45.5 GeV, σ_δ=0.0005, ν_s =0.15, τ_s =1320 turns



Loss of polarization degree due to de-phasing is small thanks to high enough ν_s.
Spin echo at synchrotron frequency are clearly visible!

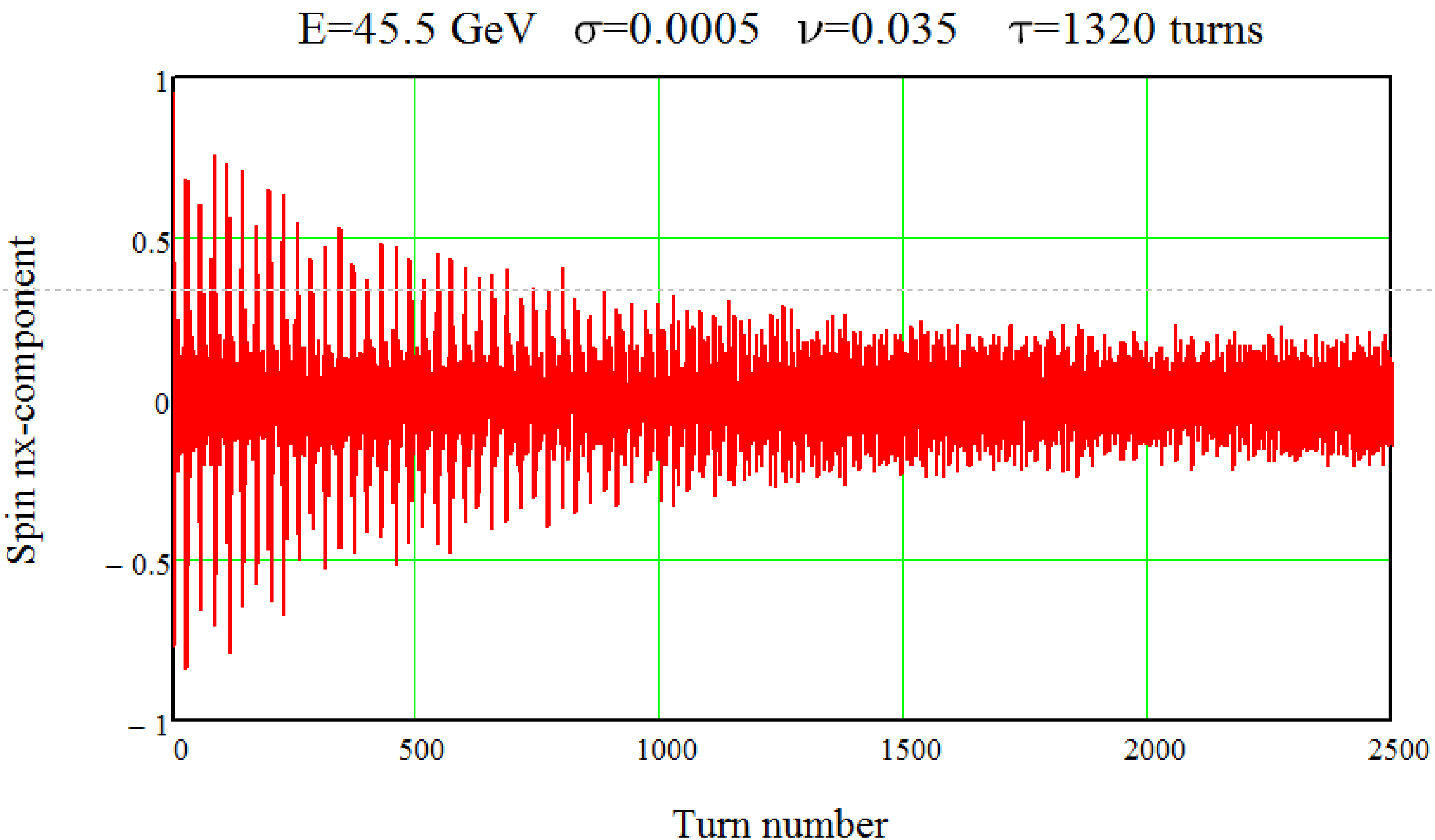
Spin precession spectrum. Number of turns 8192. E=45.5 GeV, ν_0=103.25, σ_δ=0.0005, ν_s =0.15, χ=0.35



$\chi = \sigma_\delta \nu_0/\nu_s = 0.35$ – synchrotron modulation index.

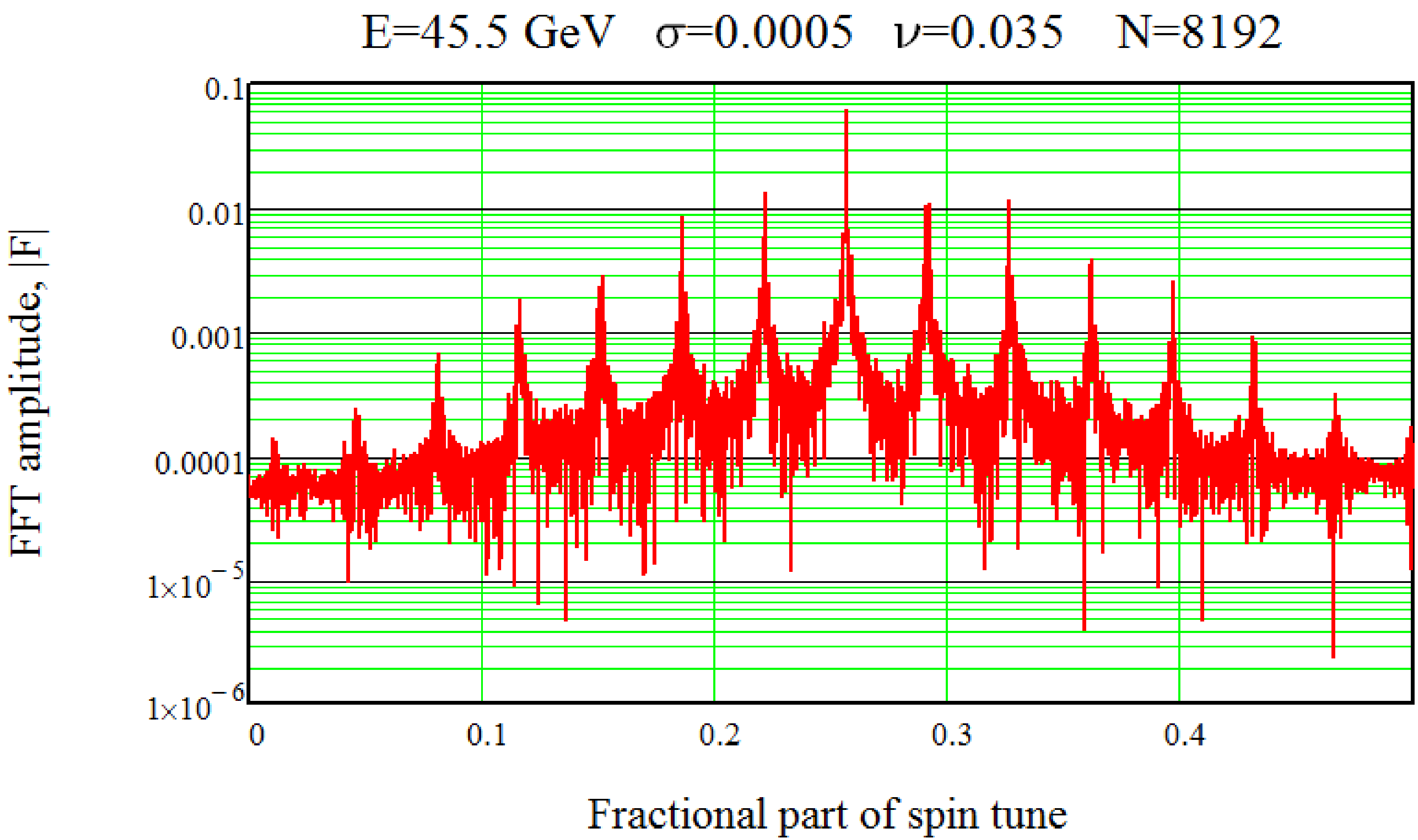
Spin tracking oscillogram. 125 test-particles.

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



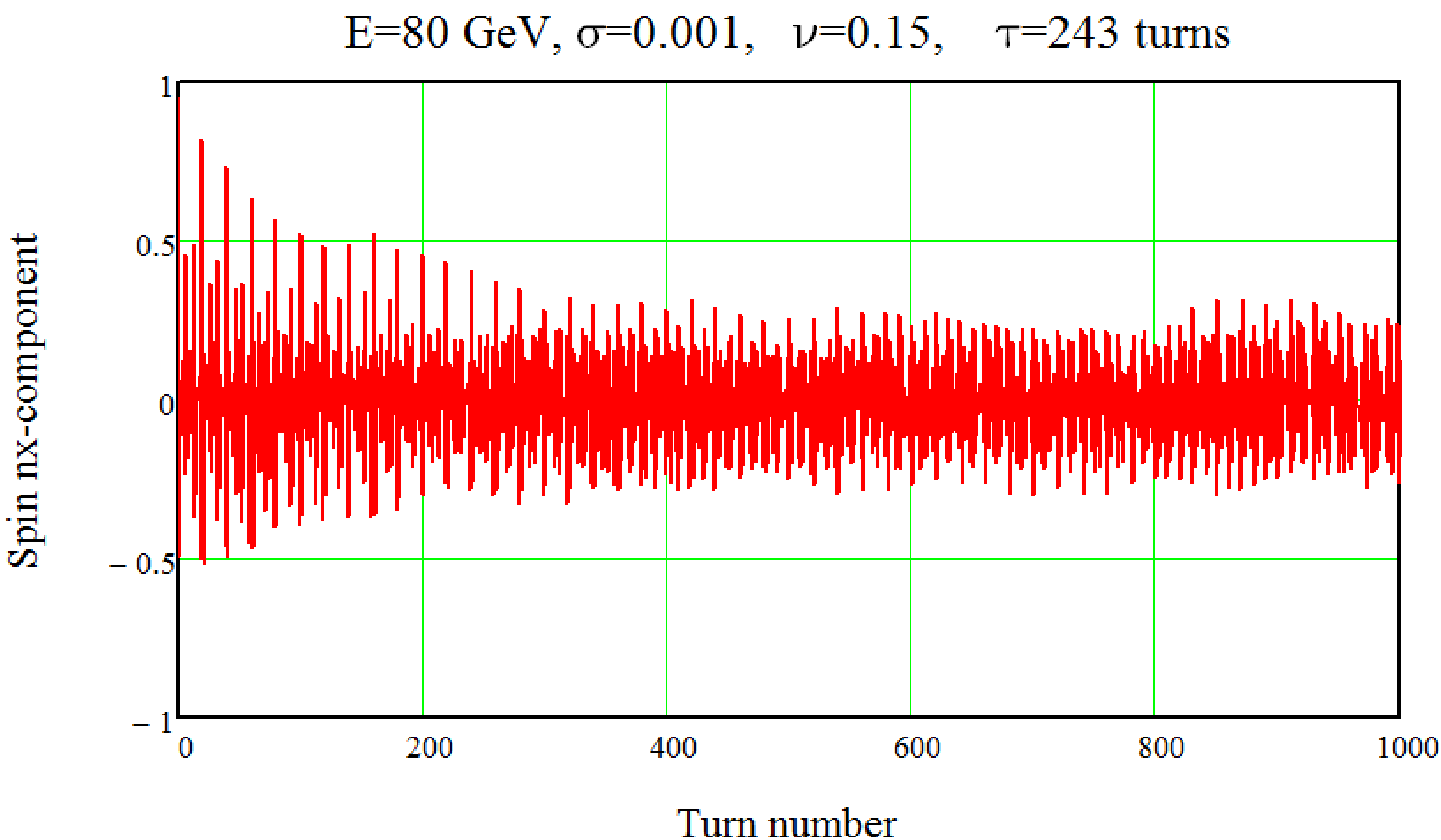
Spin precession spectrum. Number of turns 8192.

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

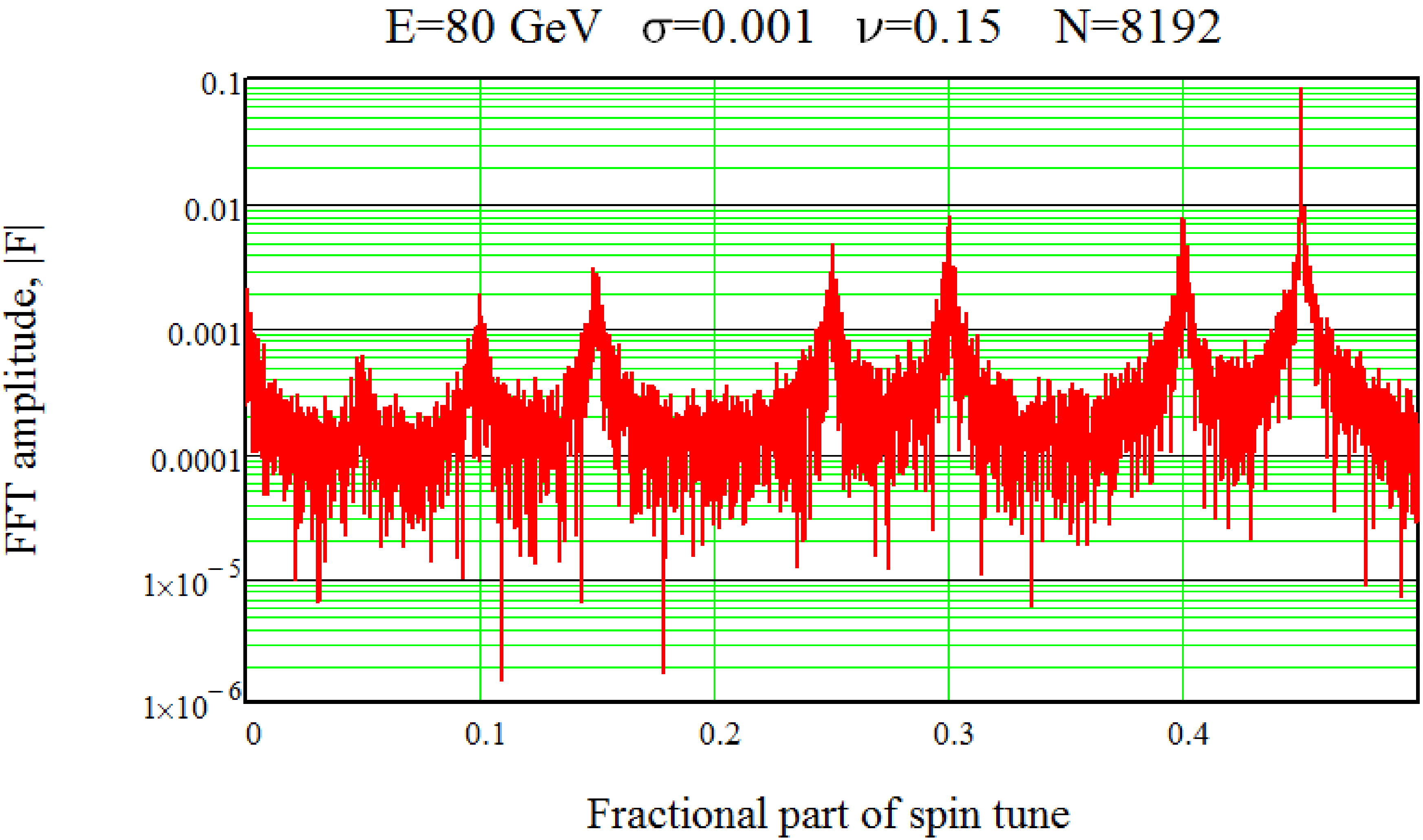


We want: $\chi < 1.7$. With $\chi > 1.7$ peaks disappear!

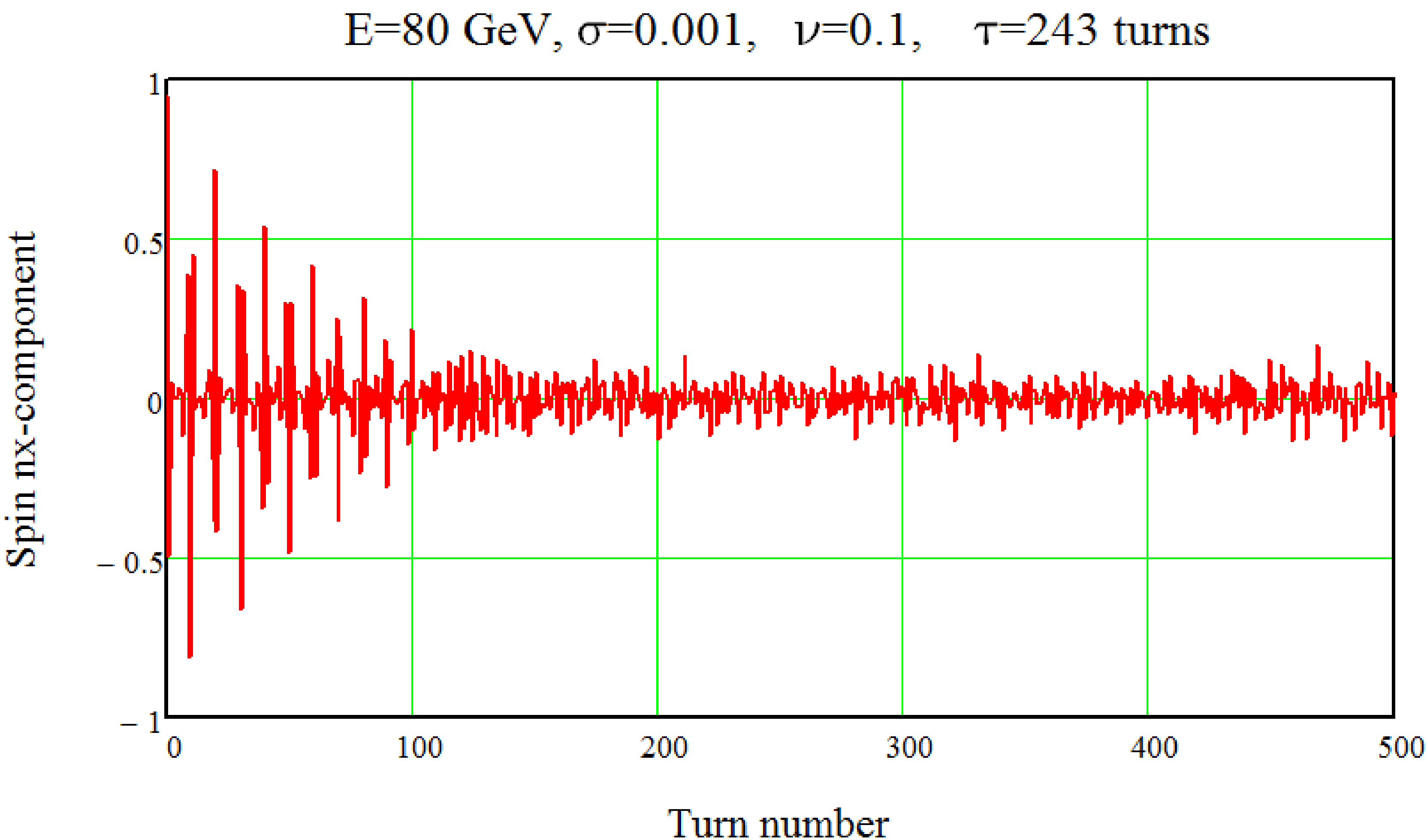
Spin tracking oscillogram. 125 test-particles.
E=80 GeV, σ_δ=0.001, ν_s =0.15, τ_s =243 turns



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

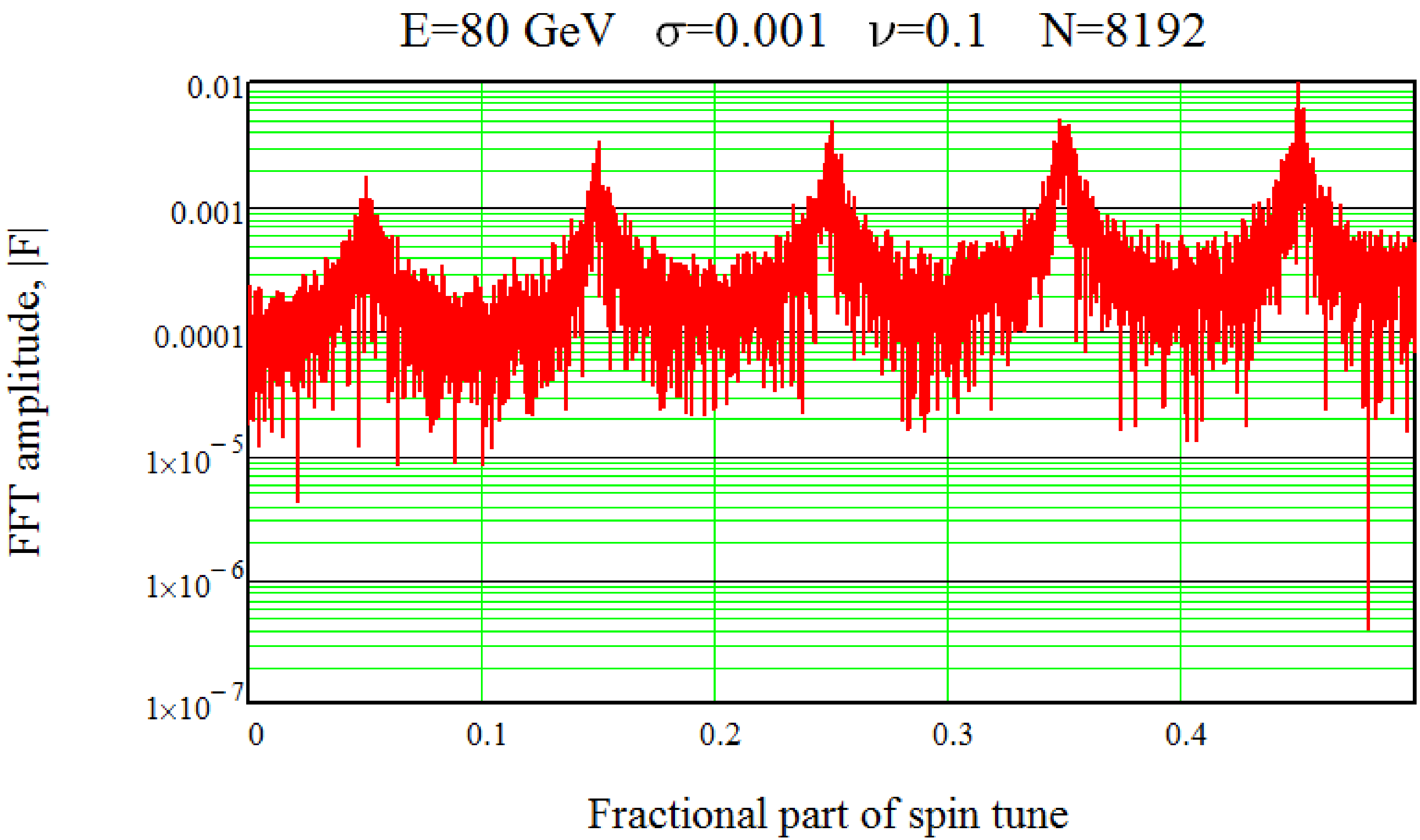


Spin tracking oscillogram. 125 test-particles.
E=80 GeV, σ_δ=0.001, ν_s =0.10, τ_s =243 turns



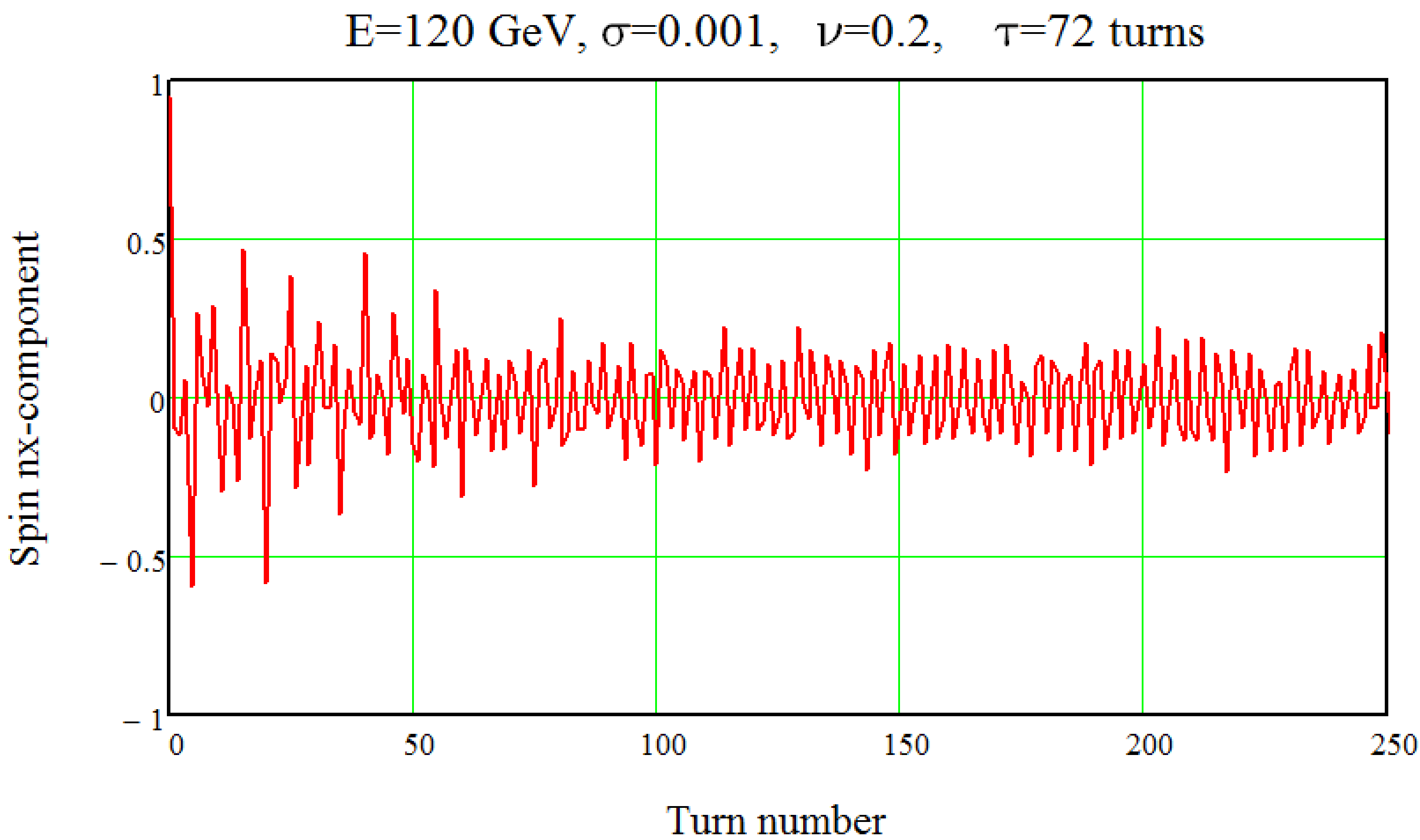
Fast de-phasing due to slow synchrotron motion!

Spin precession spectrum. Number of turns 8192. E=80 GeV, ν_0=181.55, σ_δ=0.001, ν_s =0.10, χ=1.82



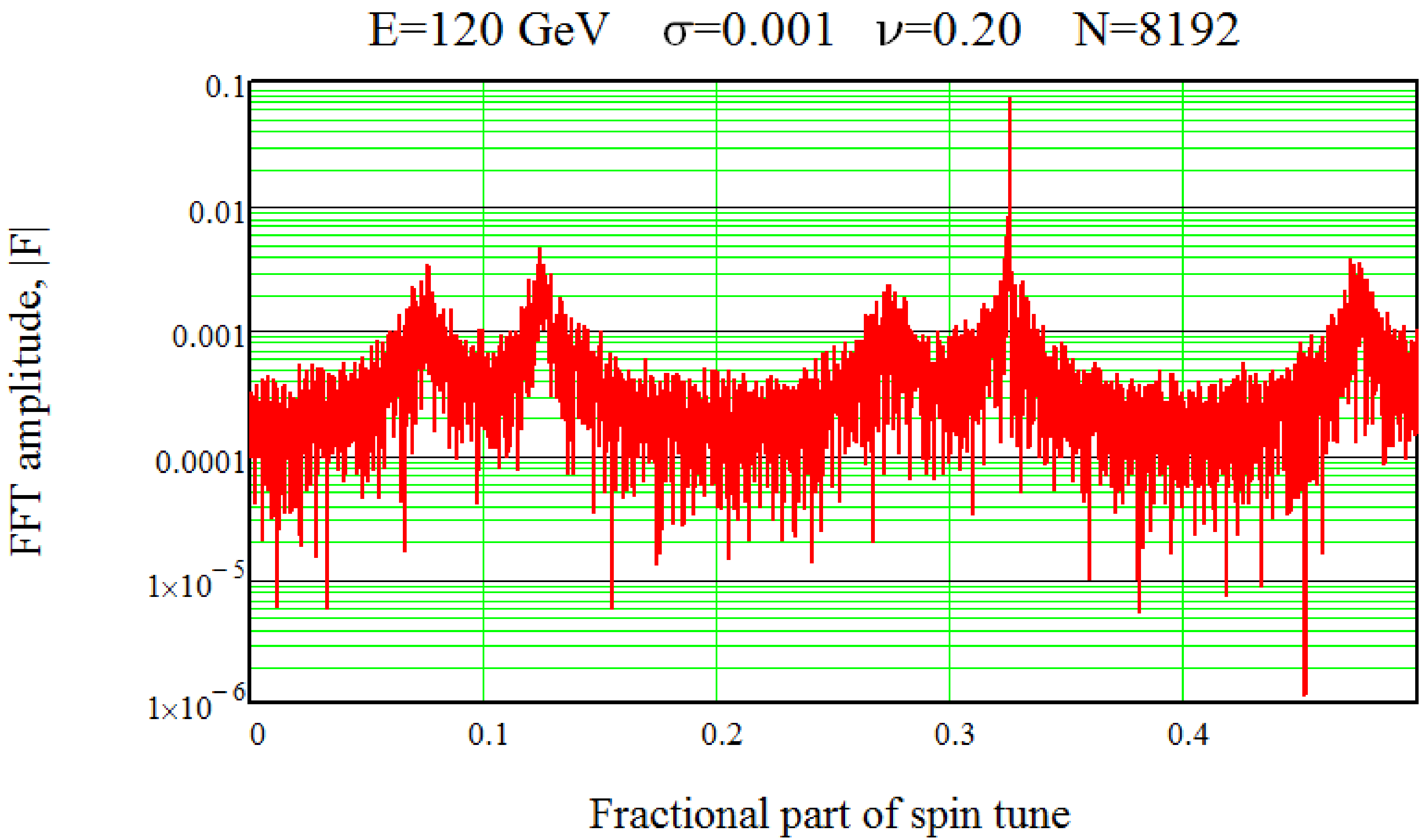
Same results one gets with doubled both: energy spread and synchrotron tune.

Spin tracking oscillogram. 125 test-particles. E=120 GeV, σ_δ=0.001, ν_s =0.20, τ_s =72 turns



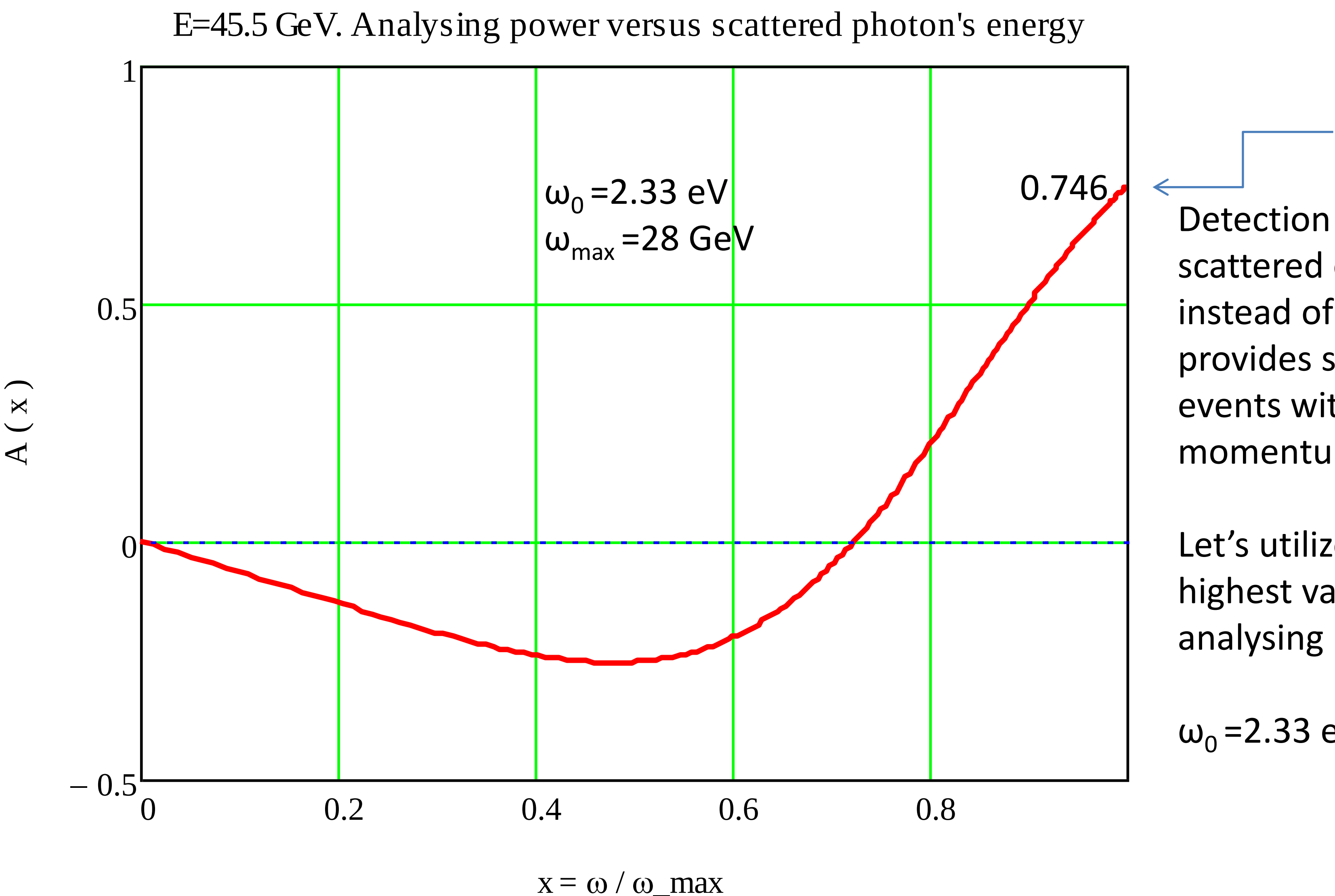
Fast de-phasing! Synchrotron modulation index is too high: χ=1.36.

Spin precession spectrum. Number of turns 8192.
E=120 GeV, ν_0=272.325, σ_δ=0.001, ν_s =0.20, χ=1.36



Same results one gets with equaly scaled energy spread and synchrotron tune.

Longitudinal polarimeter based on Compton scattering of a laser light



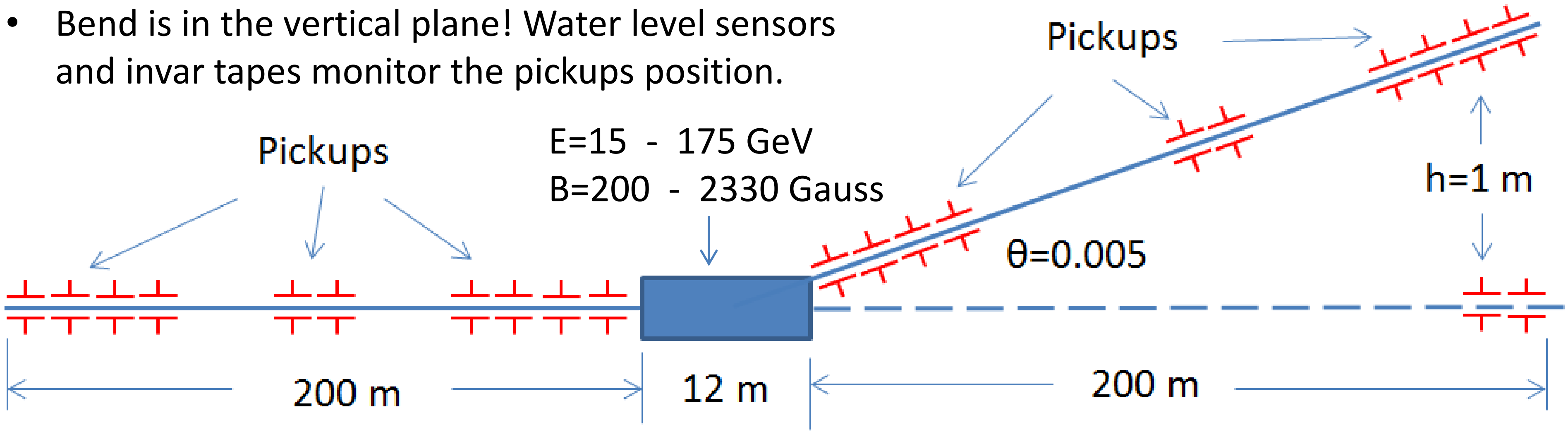
Detection of the scattered electrons instead of photons provides selection of events with maximal momentum loss!

Let's utilize the highest value of the analysing power!

ω_0 =2.33 eV

Magnetic spectrometer layout & features

- Bend is in the vertical plane! Water level sensors and invar tapes monitor the pickups position.



- Spectrometer measures the energy of the extracted beam. Advantage: much larger bending field can be applied to deflect a beam compared to the regular arc magnets.

- To get the required energy resolution in the order of 10^{-6} , the sensitivity of pickups should be in the order of 1 micron, if a beam is deflected in the end of a channel by h=1 m.

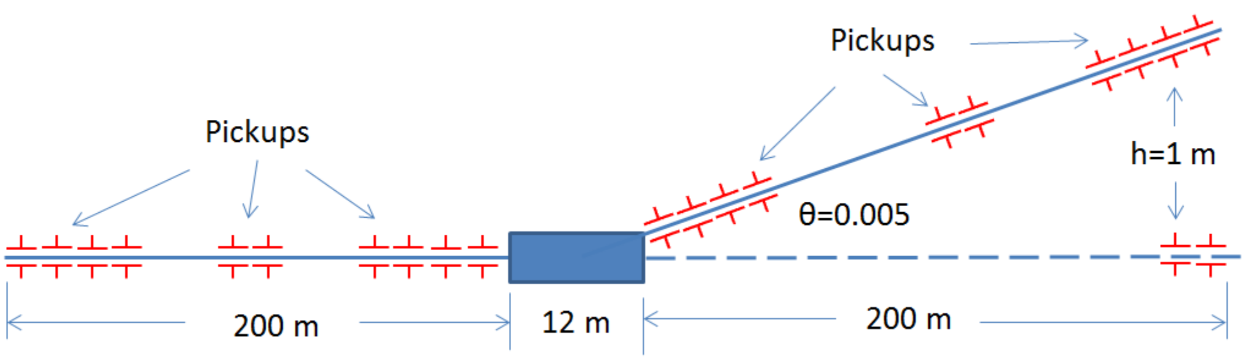
- The bending field integral should be controlled at the same level: 10^{-6} .

- No stray fields along the entire channel are permitted at same level.
- Absolute coordinates of all pickups should be measured and tracked in time with 1 micron accuracy in the transverse direction and about 200 microns along the beam path.

How to reach the required accuracies and sensitivities?

The energy resolution is required to be roughly: $\dfrac{\Delta E}{E} = \dfrac{\Delta(Bl)}{Bl} - \dfrac{\Delta h}{h} \approx 10^{-6}$

- To get the required Δh=1 mkm sensitivity, the pickups with the aperture about 1 cm shall have the electronics with 10^{-4} relative resolution.
- All pickups shall be grouped in 5-10 m long families, of 3-5 units each, to monitor their relative displacement. Cross-check between the family members! Zeros stability in time!
- Beam deflection shall be made in the vertical direction. Then one can use the well established technique of hydrostatic sensors, which have demonstrated the submicron sensitivity (FERMILAB-PUB-11-452-AD-APC-E).



- The longitudinal dimensions can be monitored by the invar tape.
- The dipole shall be made from the solid iron (more stable in time).
- Its coils shall be glued into iron, forming a solid block.
- The dipole edges should have neutral pole to be more stable in length.

- NMR probes shall monitor the magnetic field in few points along the magnet.
- Permalloy tubes supplied by the demagnetization coils shall protect the whole beam path from the Earths field.

Conclusion

- 4 Siberian snakes installed in the main booster at proper chosen locations provide preservation of the polarization during acceleration up to 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.
- 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 led to operation of the collider with high value of the synchrotron tune: $\nu_s > 0.1$ at E=80 GeV.
- The Sokolov-Ternov self-polarization mechanism requires even smaller value of the synchrotron modulation index: $\chi < 1$.
- Looks unrealistic above 80 GeV.
- A set of local energy monitors, based on well controlled magnetic spectrometers, shall be used for beam energy measurement in the full energy range of FCC-ee.