

# Accelerating and Injecting Polarized Beams in FCC-ee

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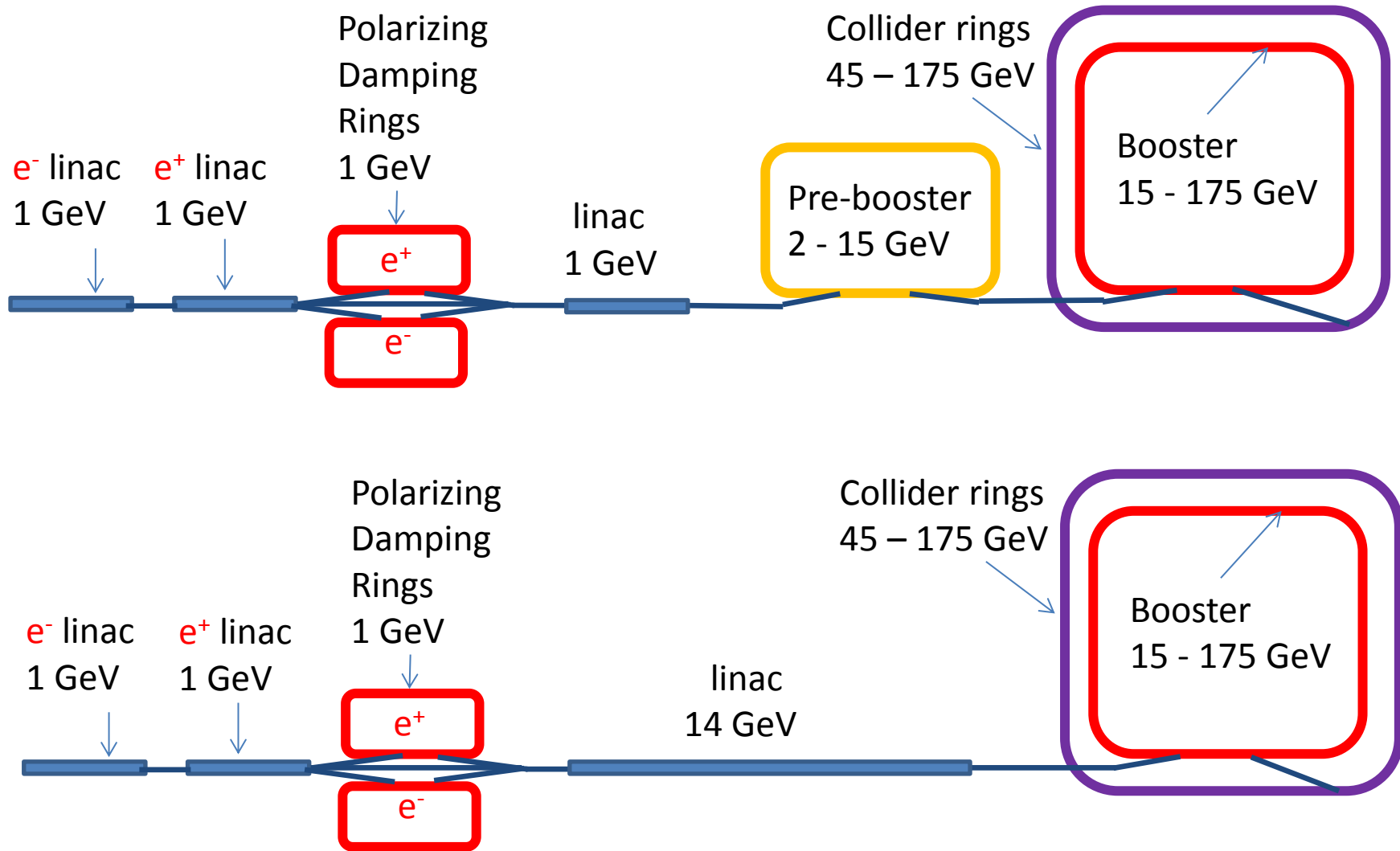
# Outline

- 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<sup>+</sup>** and **e<sup>-</sup>** 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.

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

- 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<sup>0</sup>each) .
- 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, $\rho$	0.6	m
Bending field, $B$	5.5	T
Energy loss / turn, $U_0$	145	keV
Momentum spread, $\sigma_p$	0.00155	
Number of $e^\pm$ per bunch, $N$	$10^{10}$	
Number of bunches, $N_b$	16	
Total beam current, $I$	350	mA
SR power	50	kW
Polarization time (Sokolov-Ternov), $\tau_{ST}$	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.

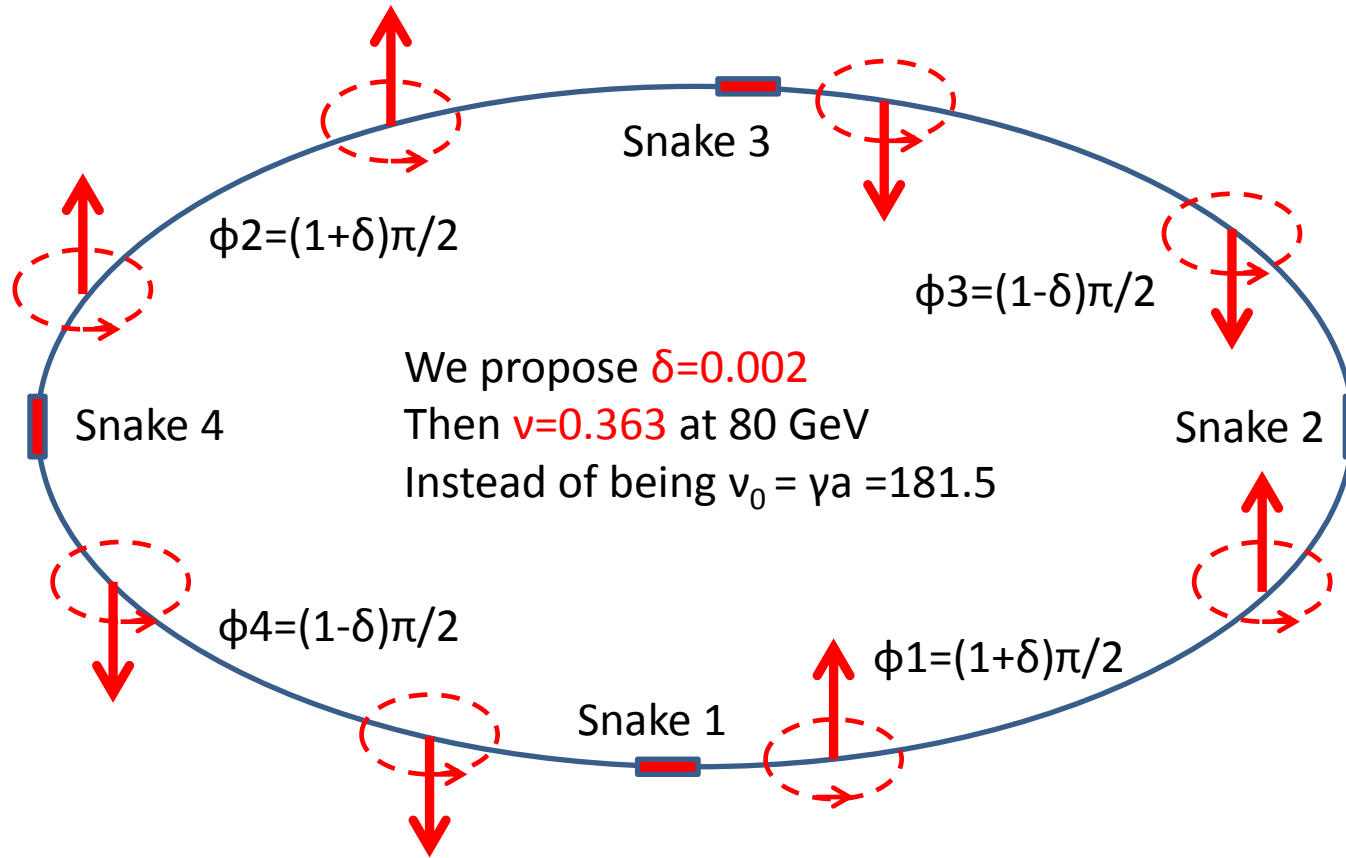
Use of high bending field is energetically beneficial to obtain certain polarization degree.

# High energy booster synchrotron demands

- Fast acceleration from 15 GeV up to 175 GeV train of unpolarized  $e^\pm$  bunches to keep the collider luminosity constant within  $\pm 5\%$  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



We propose  $\delta=0.002$   
 Then  $v=0.363$  at 80 GeV  
 Instead of being  $v_0 = \gamma a = 181.5$

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.

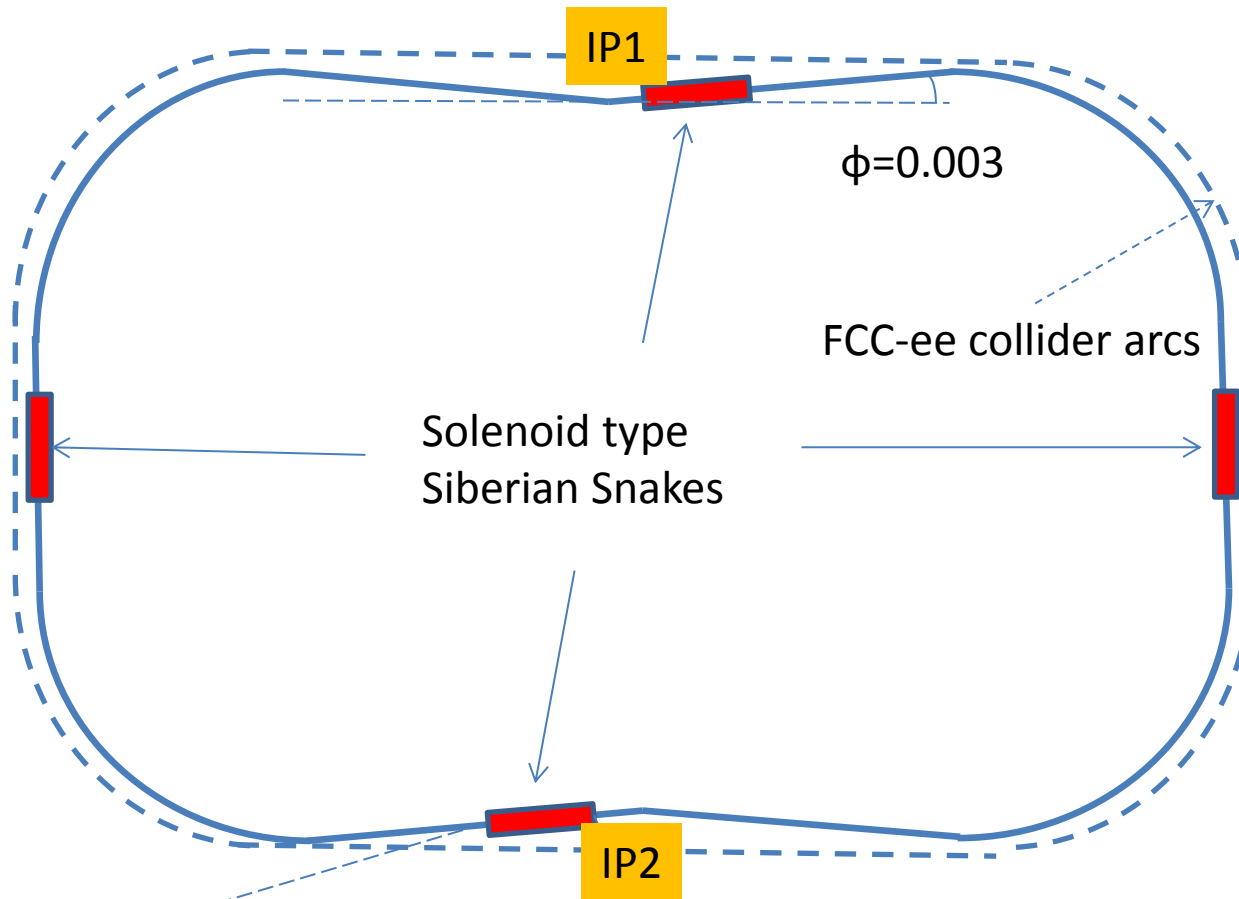
The equilibrium spin direction is upright or down in arcs.

Snakes rotate spin by  $180^\circ$  around the longitudinal direction.

The spin precession frequency will be zero in case of equally spaced snakes.

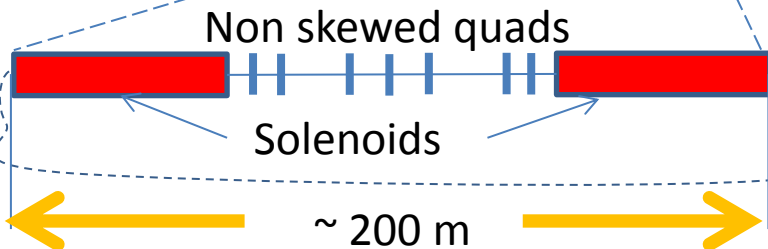
To make the spin motion stable a small asymmetry of “positive” and “negative” arcs has to be foreseen:  $\phi=(1\pm\delta)\pi/2$ . Then the spin tune became reduced to  $v= \delta \cdot v_0$ . Here  $v_0=\gamma a$  – unperturbed spin tune, with  $a=0.001159652187\dots$  - the anomalous magnetic moment.

# 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:

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

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

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

For  $m$  pairs of snakes  $\langle \vec{d}^2 \rangle \sim v_0^2 w^2 / m^2$ , Here  $v_0 = \gamma a$ ,

$w$  - 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  $\langle \vec{d}^2 \rangle \simeq 4000 \rightarrow \tau_d \approx 18$  s

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

# Tolerances on the orbit distortions

Tolerances on the vertical orbit distortion  $y(s)$ :

Spin rotation angle kick produced by a single quad:  $\varphi_1 = v_0 \cdot \Delta y_1'$

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

Statistically independent  $N$  kicks will produce the total spin rotation:

$$\varphi_\Sigma \approx v_0 \cdot \Delta y_1' \cdot \sqrt{N} \quad \text{Now we want: } \varphi_\Sigma \leq w \cdot 2\pi,$$

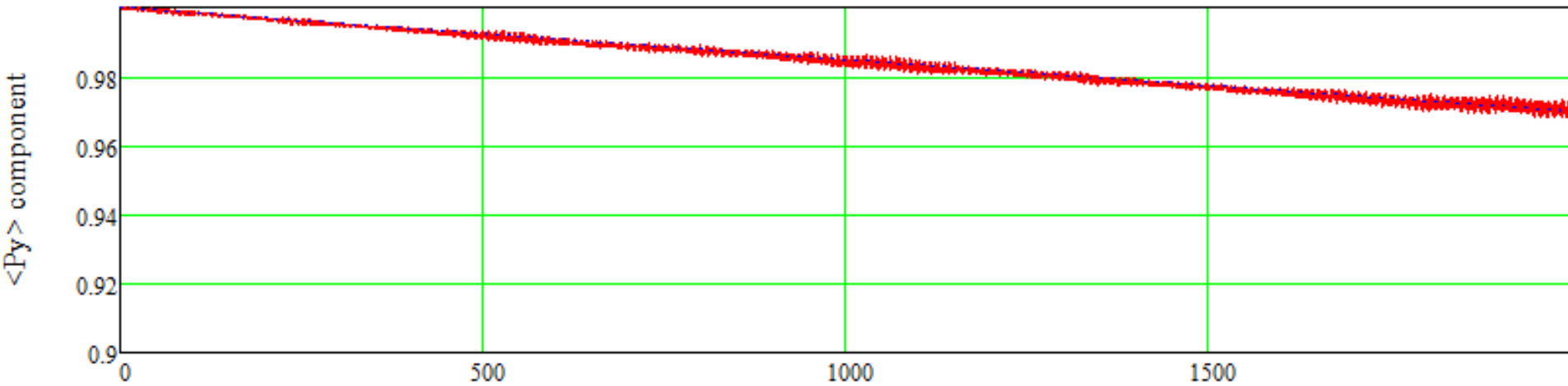
Here  $w$  - single equivalent by strength the spin perturbation tune

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

$$\text{Thus we get: } \Delta y_1' \leq \frac{w \cdot 2\pi}{v_0 \cdot \sqrt{N}} \approx 6 \cdot 10^{-5} \quad \rightarrow \quad y_{\text{rms}} \approx \Delta y_1' \cdot \beta_y \approx 6 \text{ mm}$$

# Spin tracking of the depolarization process

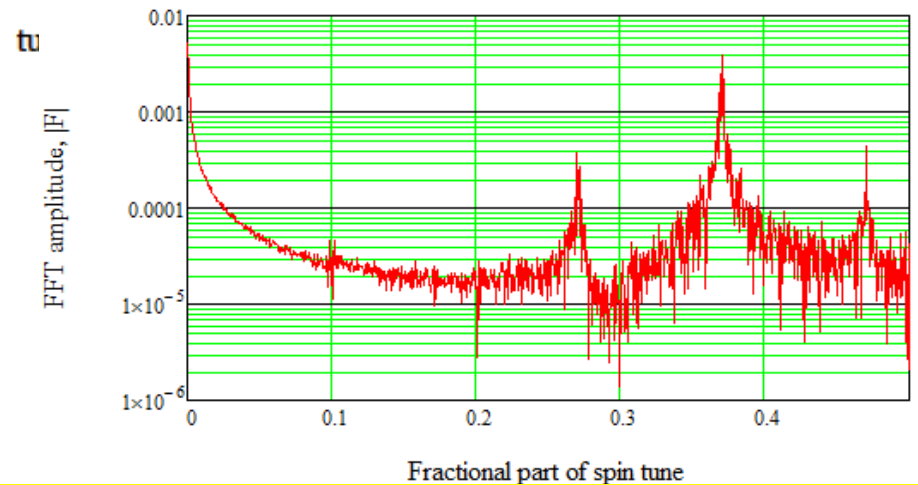
Radiative depolarization: 4 snakes, 80 GeV,  $\sigma_E=0.00065$ ,  $\lambda=1/240$ ,  $\nu=0.363$ , perturbation  $w=0.1$



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.

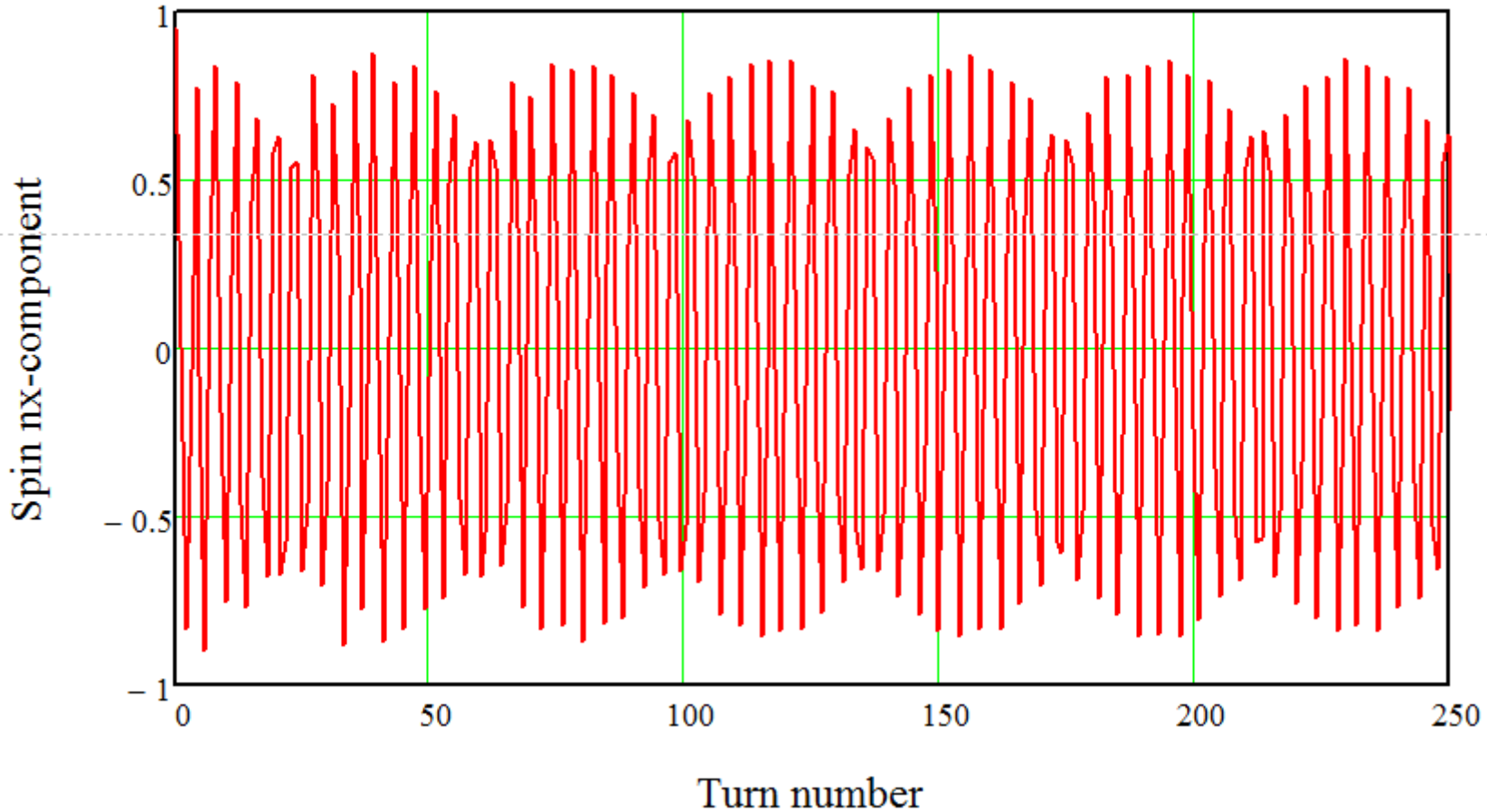


Spectrum of the transversal polarization component. Side bands are spaced by synchrotron tune  $\nu_s=0.1$

# Spin tracking oscillogram. 125 test-particles.

$E=45.5$  GeV,  $\sigma_\delta=0.0005$ ,  $\nu_s=0.15$ ,  $\tau_s=1320$  turns

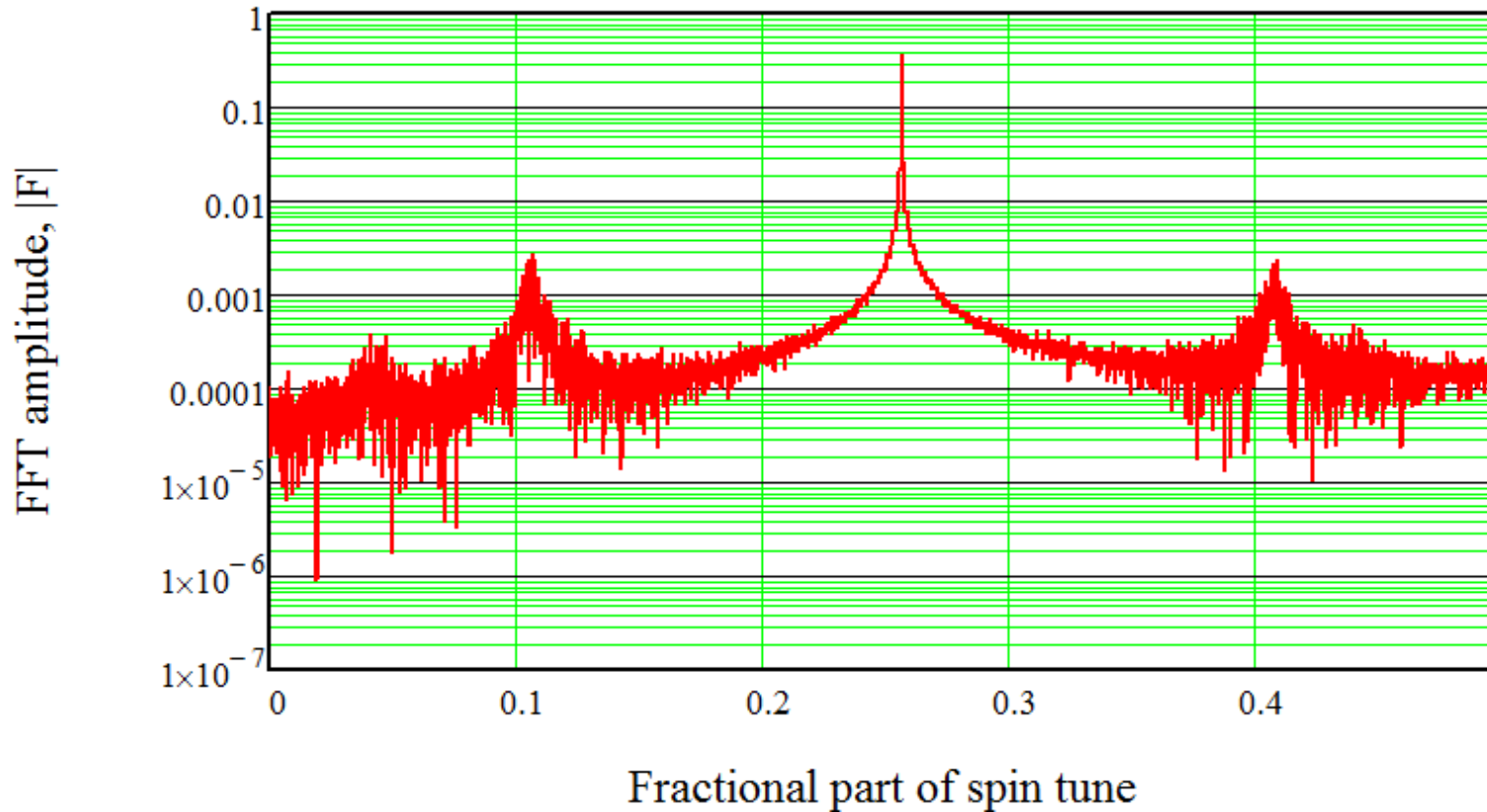
$E=45.5$  GeV  $\sigma=0.0005$   $\nu=0.15$



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

Spin precession spectrum. Number of turns 8192.  
 $E=45.5$  GeV,  $\nu_0=103.25$ ,  $\sigma_\delta=0.0005$ ,  $\nu_s=0.15$ ,  $\chi=0.35$

$E=45.5$  GeV  $\sigma=0.0005$   $\nu=0.15$   $N=8192$

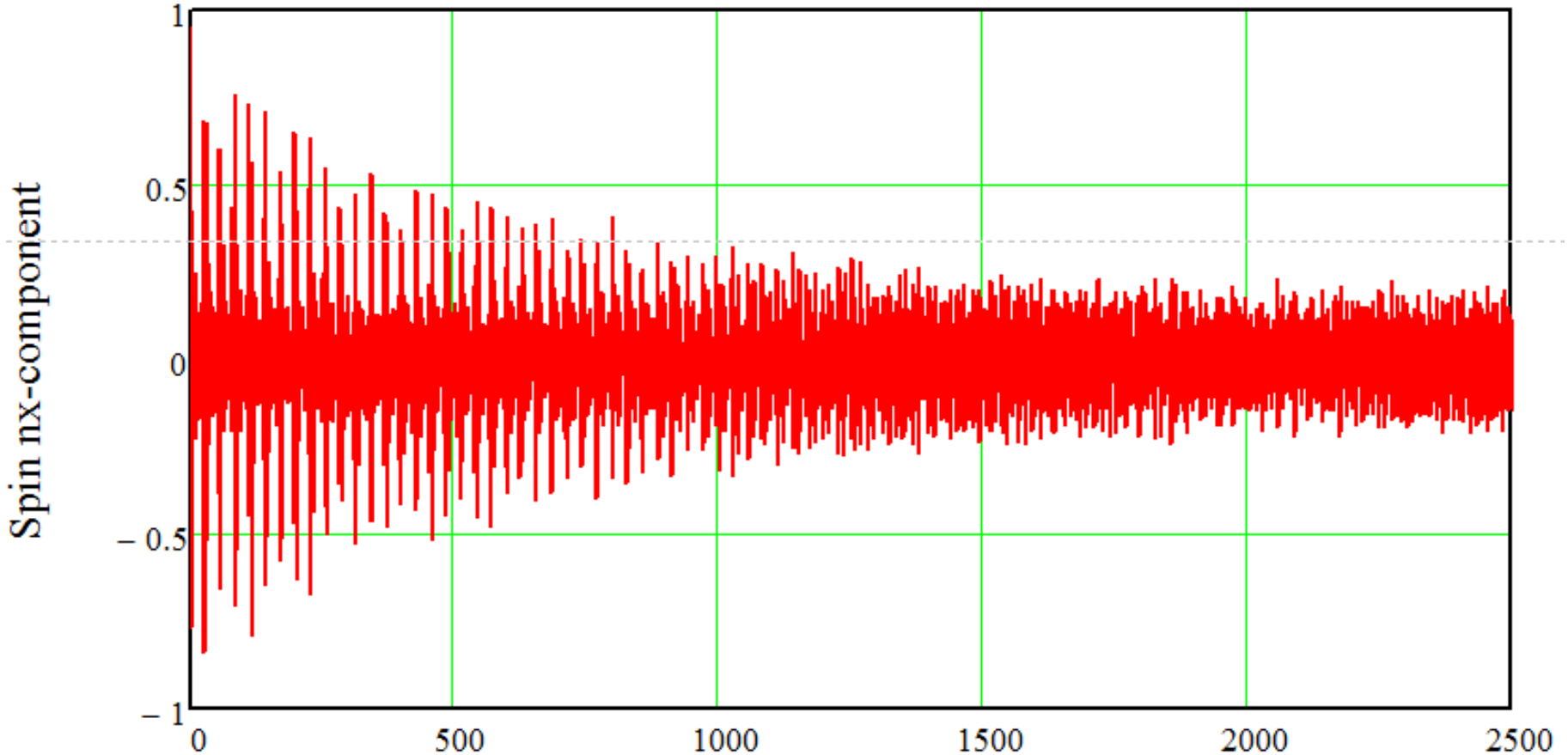


$\chi = \sigma_\delta \nu_0 / \nu_s = 0.35$  – synchrotron modulation index.

# Spin tracking oscillogram. 125 test-particles.

$E=45.5$  GeV,  $\sigma_\delta=0.0005$ ,  $\nu_s=0.035$ ,  $\tau_s=1320$  turns

$E=45.5$  GeV  $\sigma=0.0005$   $\nu=0.035$   $\tau=1320$  turns



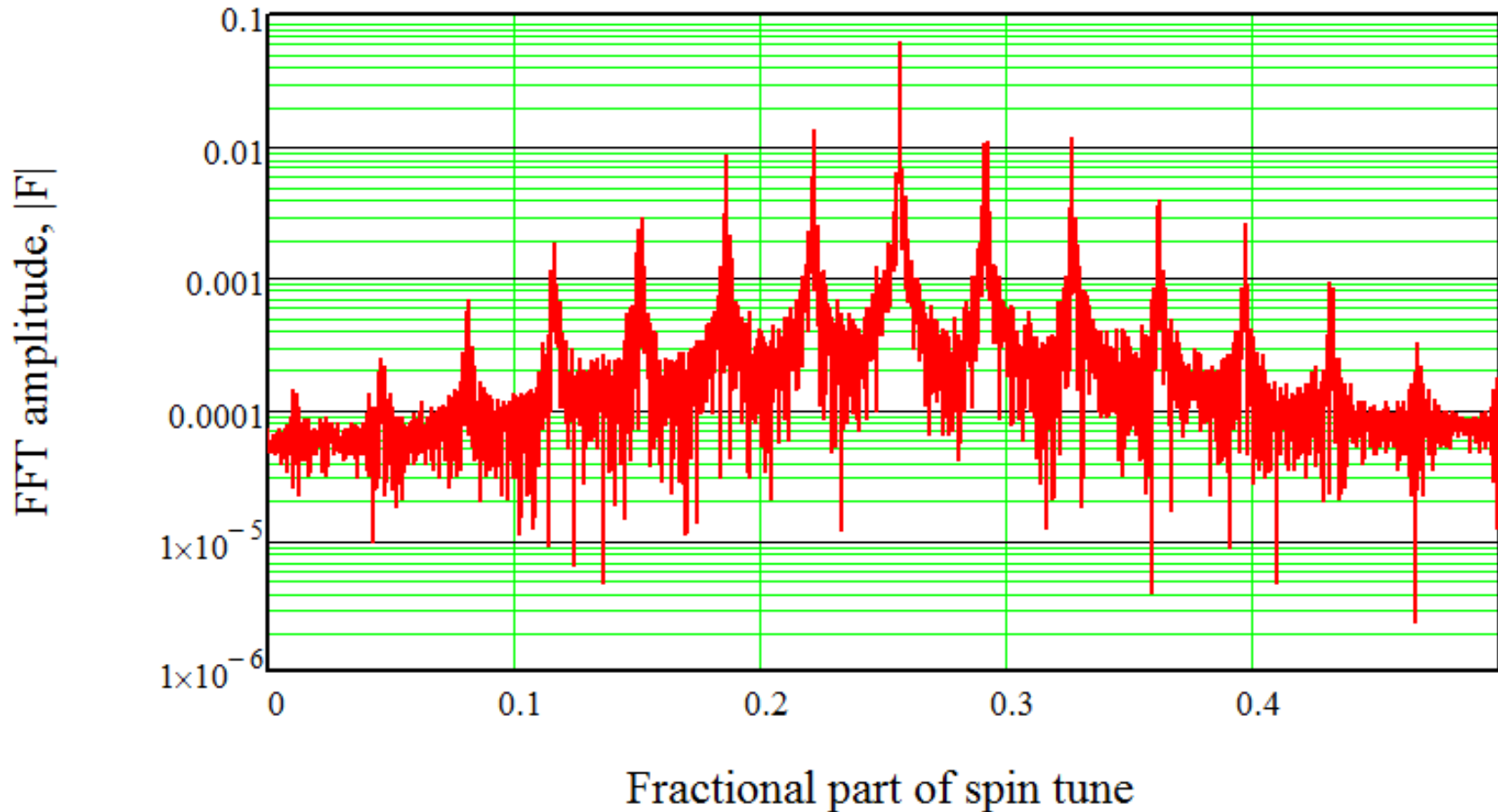
Turn number

Koop-Acceleration



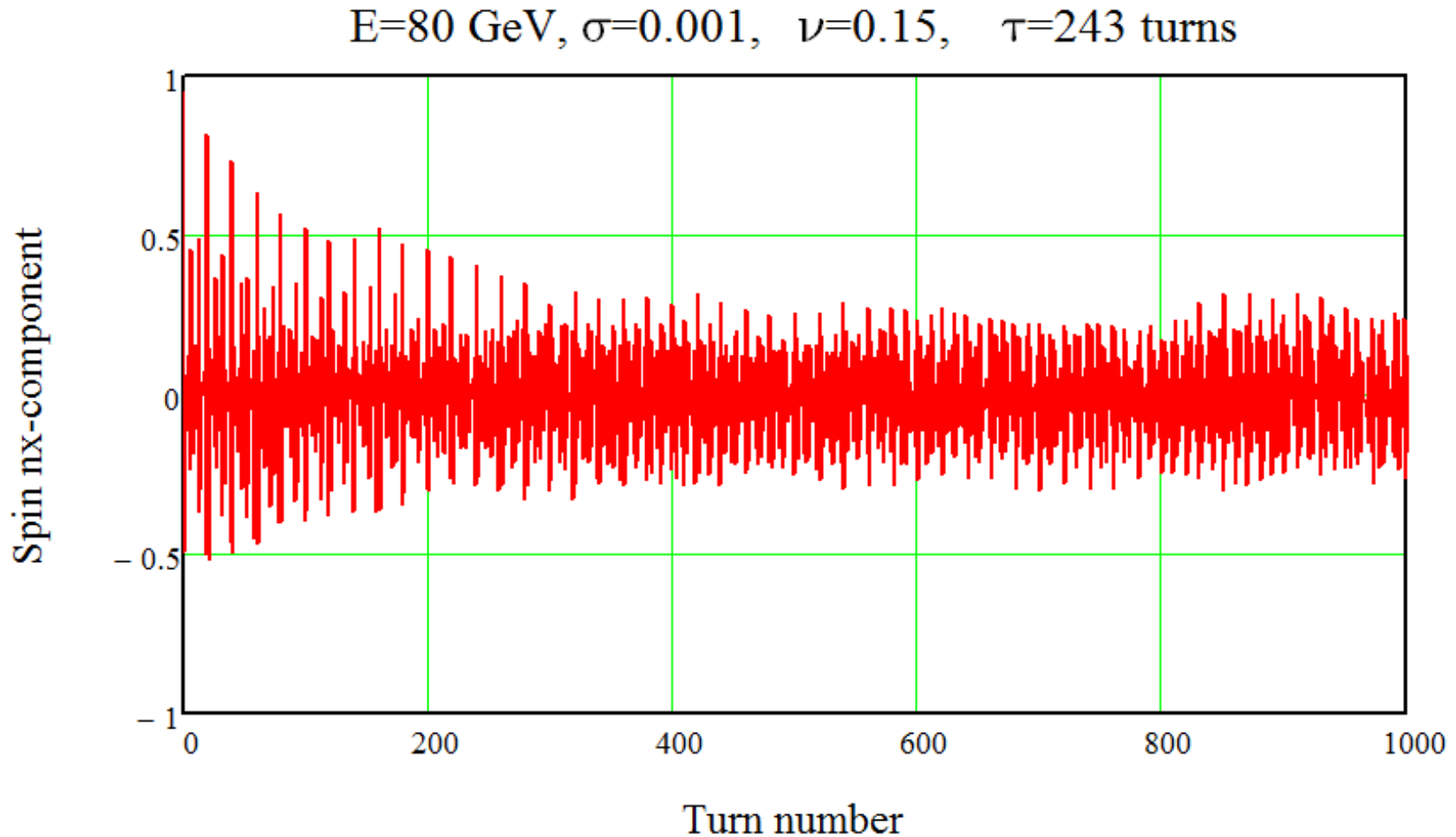
Spin precession spectrum. Number of turns 8192.  
 $E=45.5$  GeV,  $\nu_0=103.25$ ,  $\sigma_\delta=0.0005$ ,  $\nu_s=0.035$ ,  $\chi=1.48$

$E=45.5$  GeV  $\sigma=0.0005$   $\nu=0.035$   $N=8192$



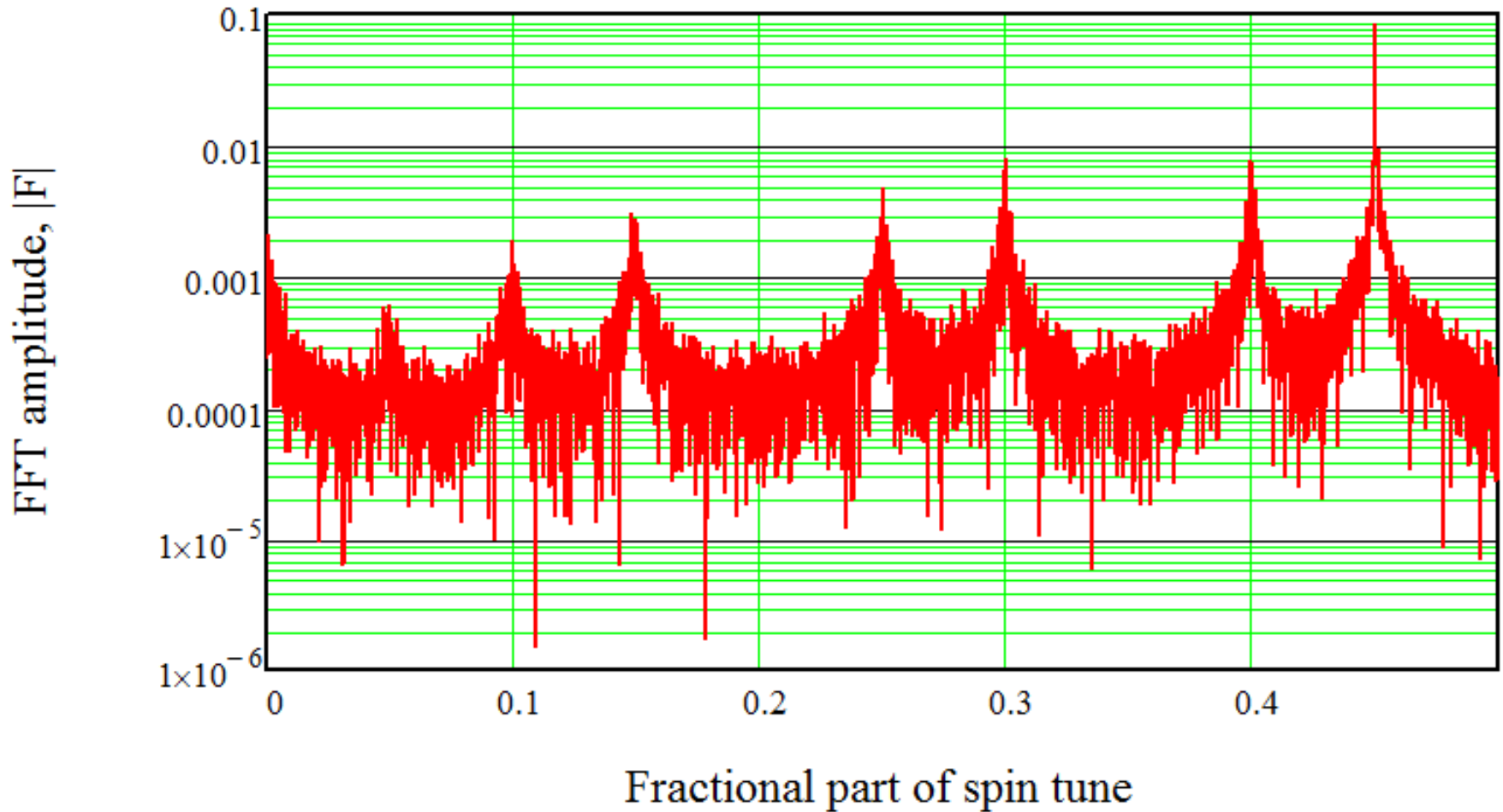
We want:  $\chi < 1.7$ . With  $\chi > 1.7$  peaks disappear!

Spin tracking oscillogram. 125 test-particles.  
 $E=80$  GeV,  $\sigma_\delta=0.001$ ,  $\nu_s=0.15$ ,  $\tau_s=243$  turns

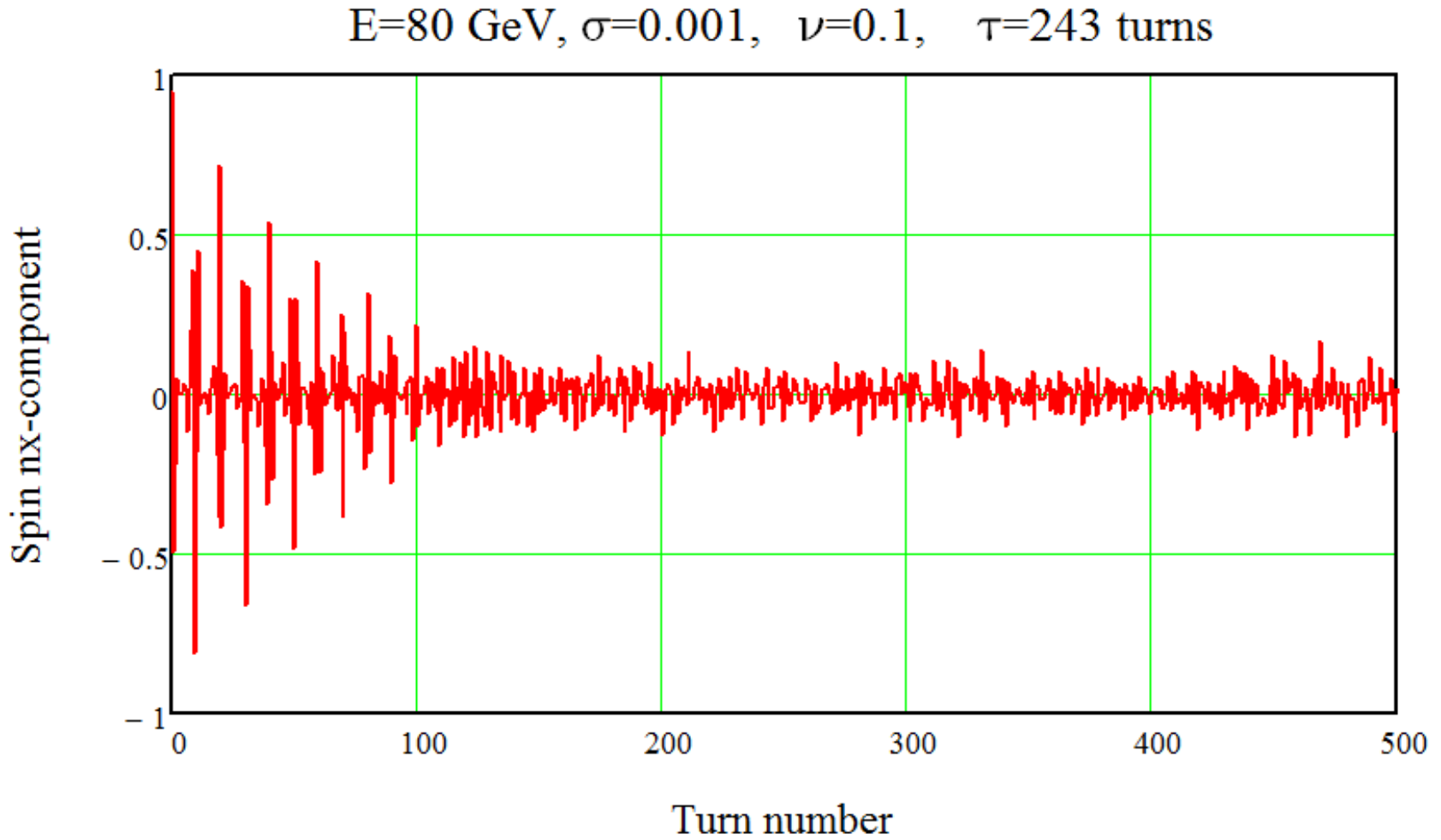


Spin precession spectrum. Number of turns 8192.  
 $E=80$  GeV,  $\nu_0=181.55$ ,  $\sigma_\delta=0.001$ ,  $\nu_s=0.15$ ,  $\chi=1.21$

$E=80$  GeV  $\sigma=0.001$   $\nu=0.15$   $N=8192$



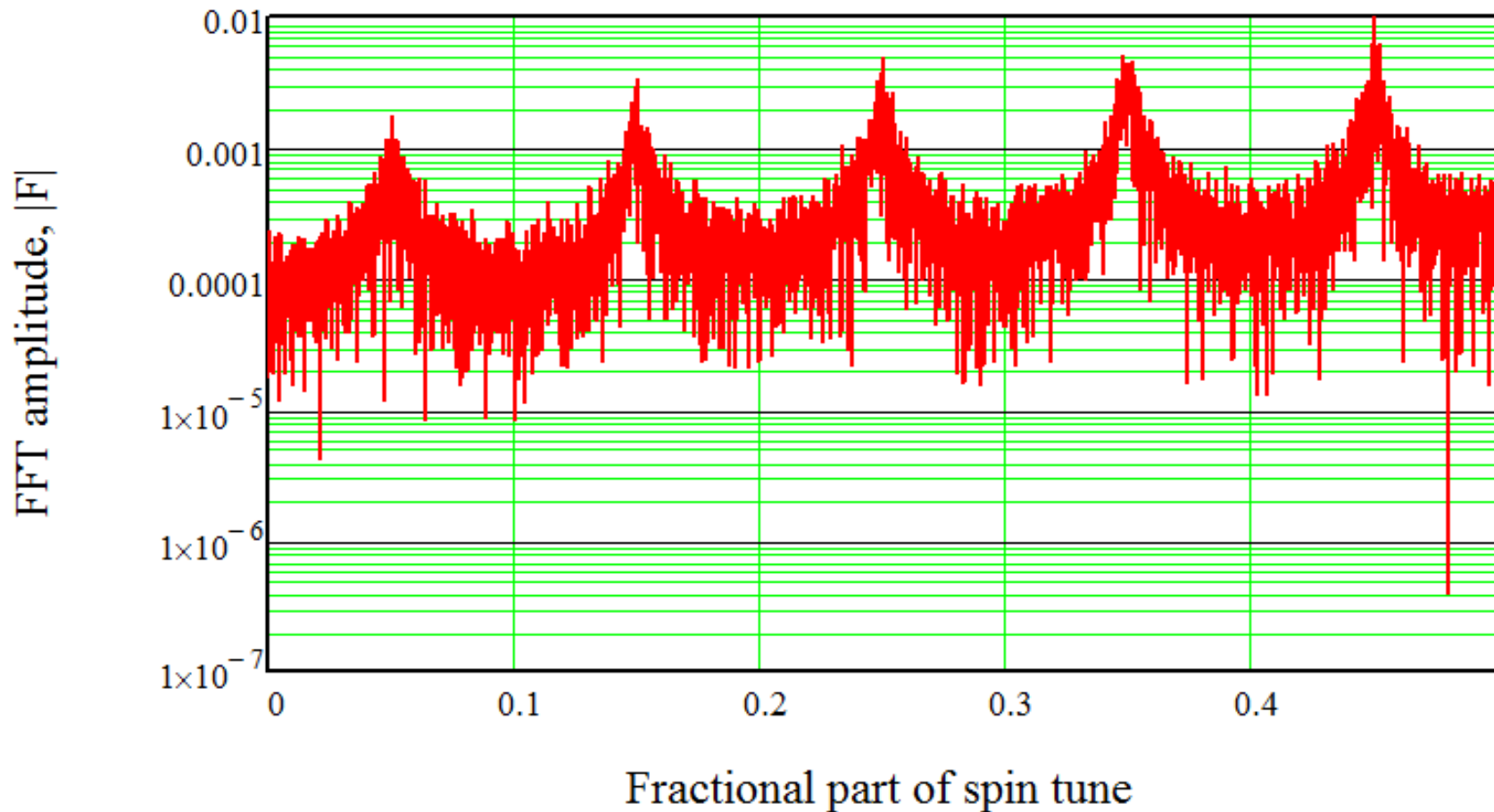
Spin tracking oscillogram. 125 test-particles.  
 $E=80$  GeV,  $\sigma_\delta=0.001$ ,  $\nu_s=0.10$ ,  $\tau_s=243$  turns



Fast de-phasing due to slow synchrotron motion!

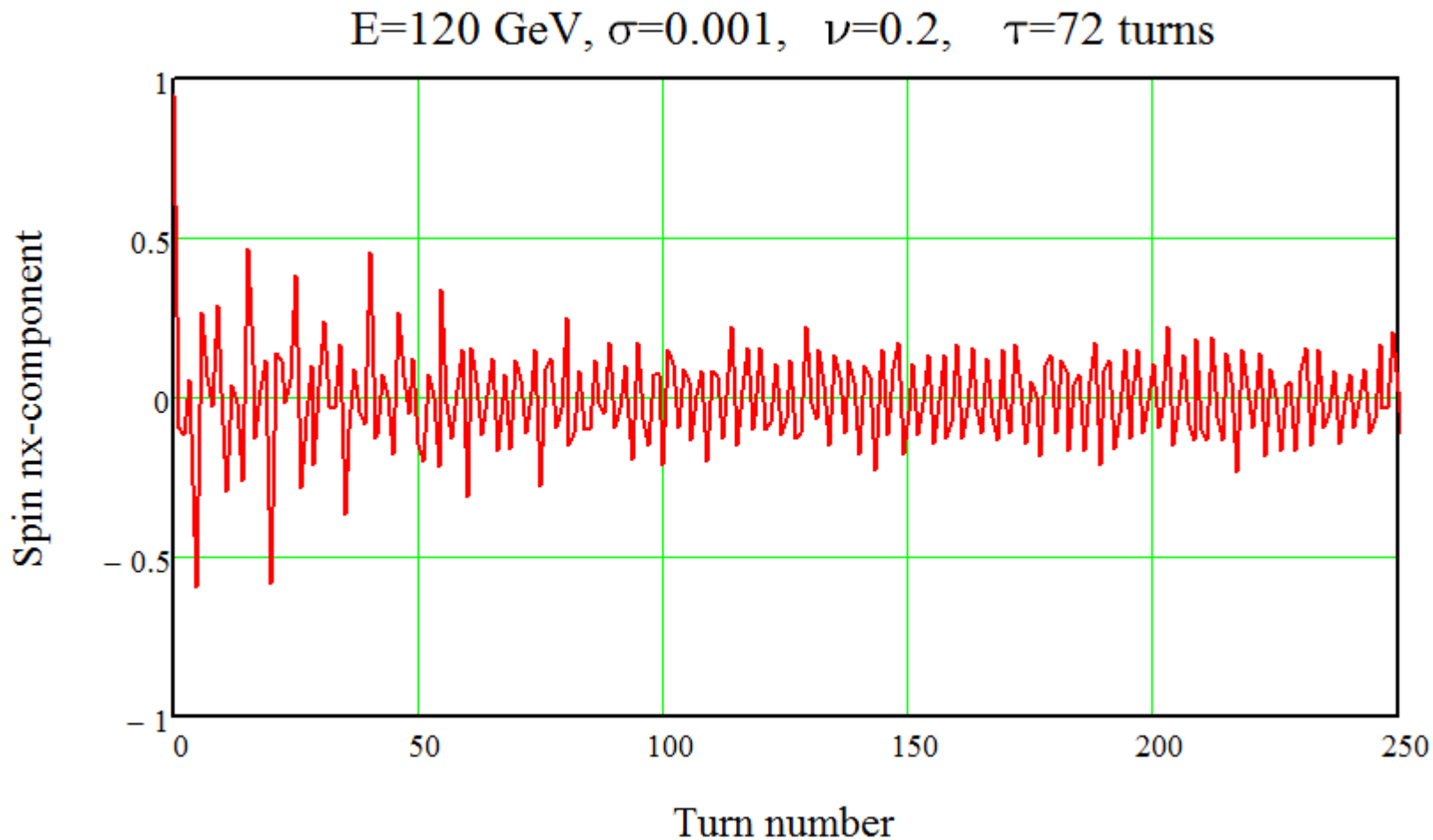
Spin precession spectrum. Number of turns 8192.  
 $E=80$  GeV,  $\nu_0=181.55$ ,  $\sigma_\delta=0.001$ ,  $\nu_s=0.10$ ,  $\chi=1.82$

$E=80$  GeV  $\sigma=0.001$   $\nu=0.1$   $N=8192$



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

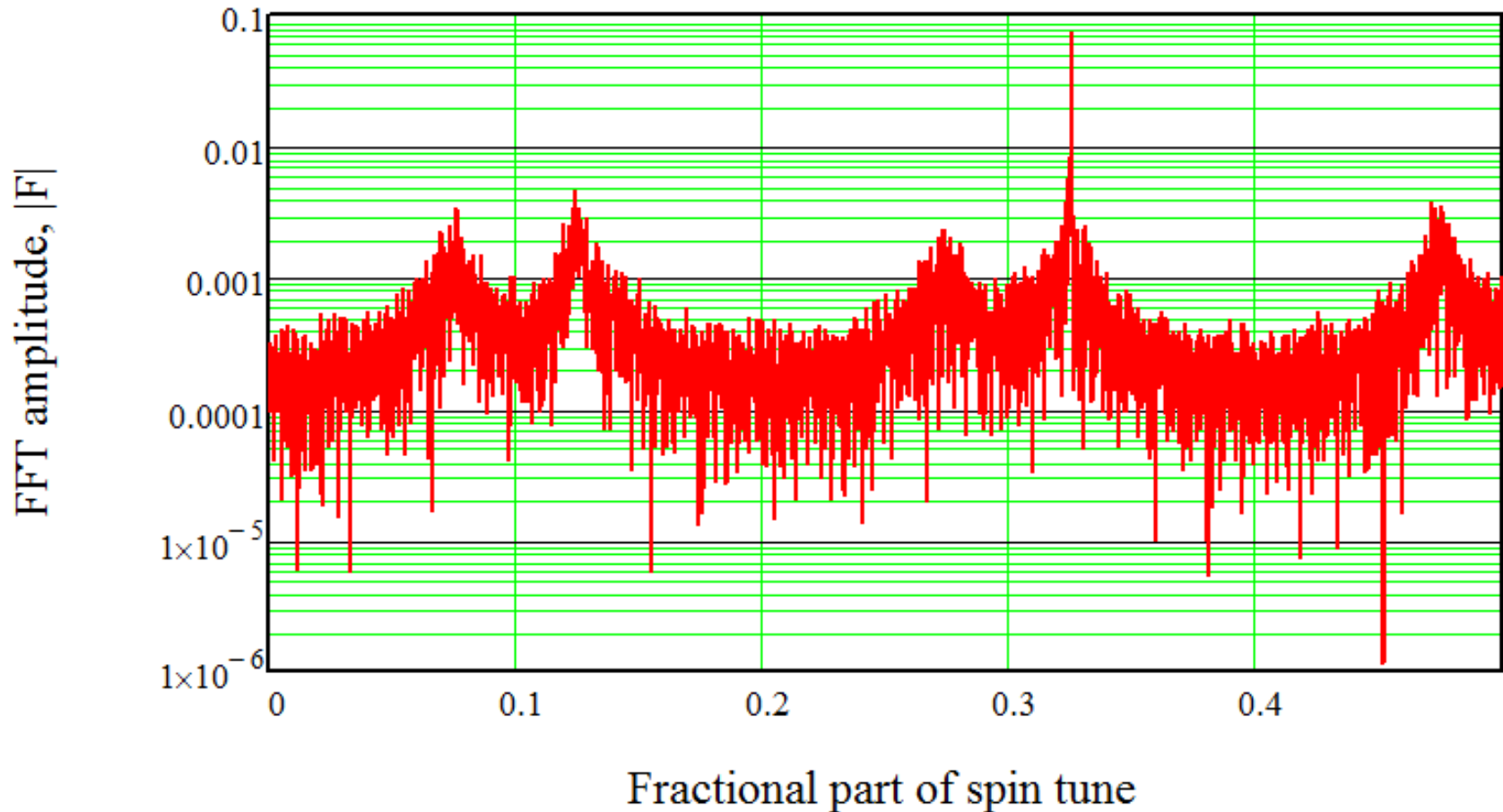
Spin tracking oscillogram. 125 test-particles.  
 $E=120$  GeV,  $\sigma_\delta=0.001$ ,  $\nu_s=0.20$ ,  $\tau_s=72$  turns



Fast de-phasing! Synchrotron modulation index is too high:  $\chi=1.36$ .

Spin precession spectrum. Number of turns 8192.  
 $E=120$  GeV,  $\nu_0=272.325$ ,  $\sigma_\delta=0.001$ ,  $\nu_s=0.20$ ,  $\chi=1.36$

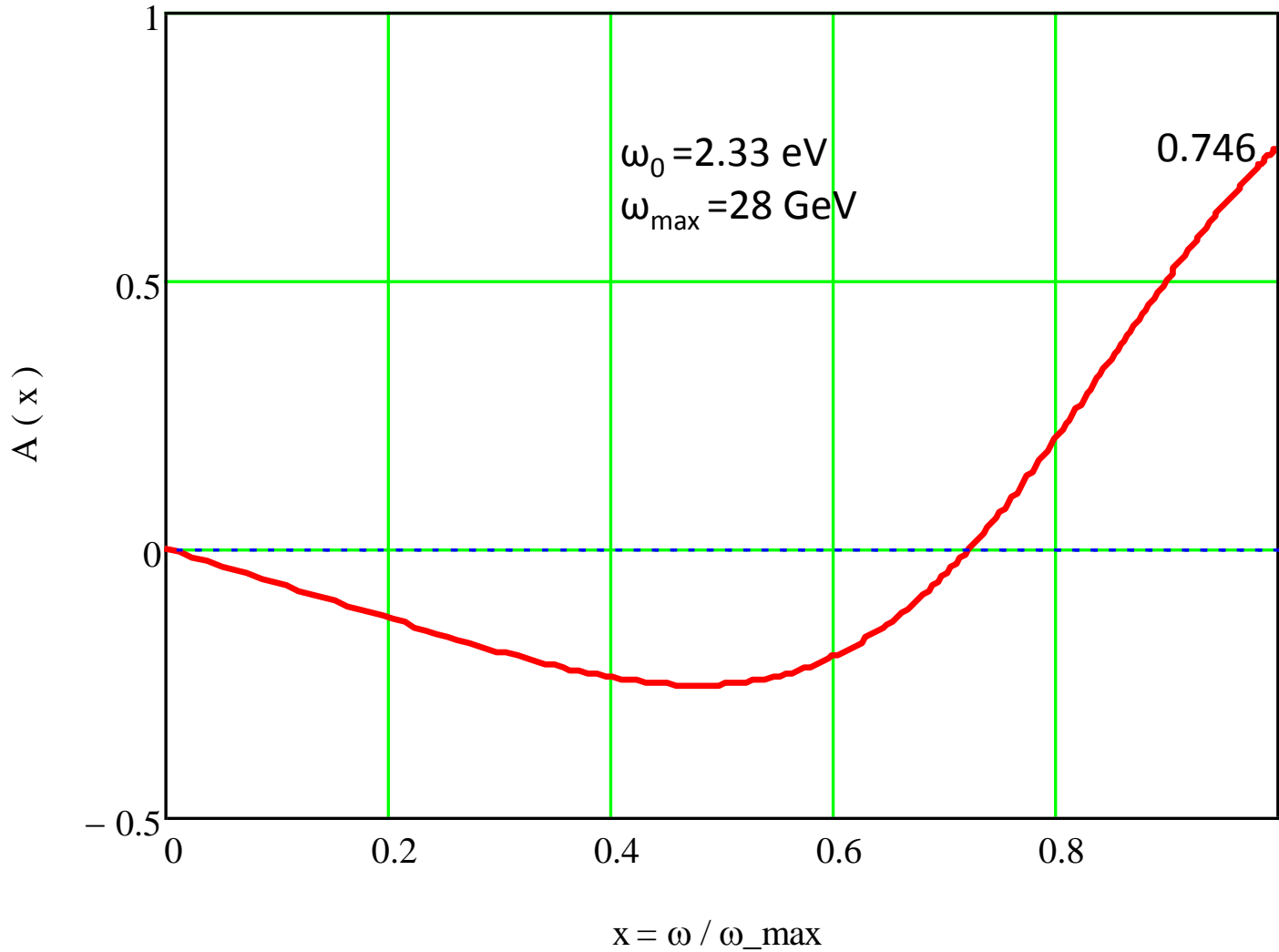
$E=120$  GeV  $\sigma=0.001$   $\nu=0.20$   $N=8192$



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

# Longitudinal polarimeter based on Compton scattering of a laser light

$E=45.5$  GeV. Analysing power versus scattered photon's energy



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

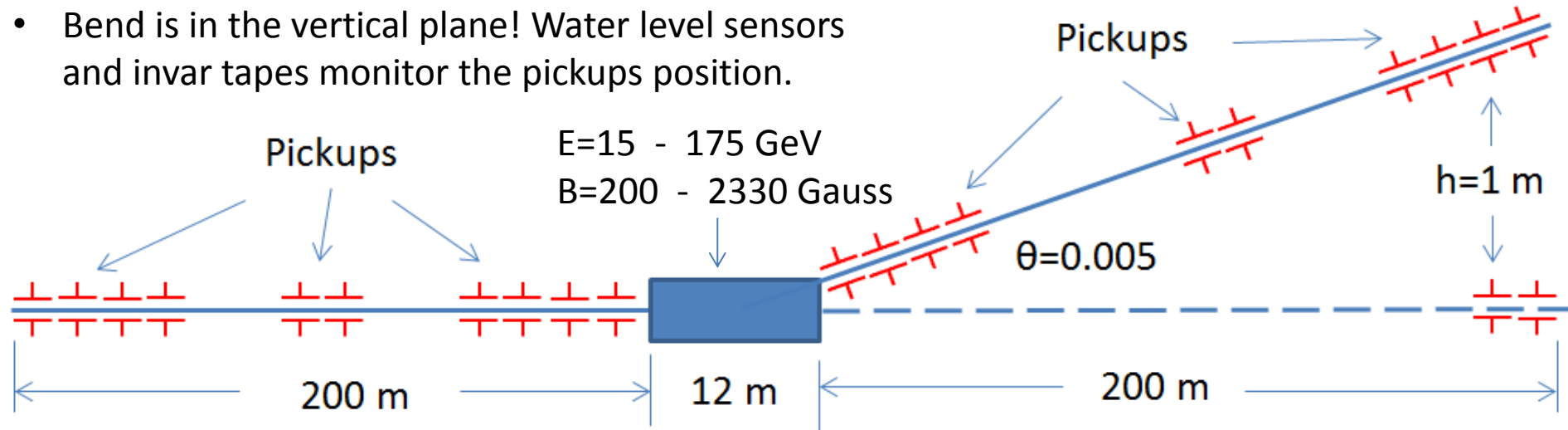
Let's utilize the highest value of the analysing power!

$\omega_0 = 2.33$  eV



# Magnetic spectrometer layout & features

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

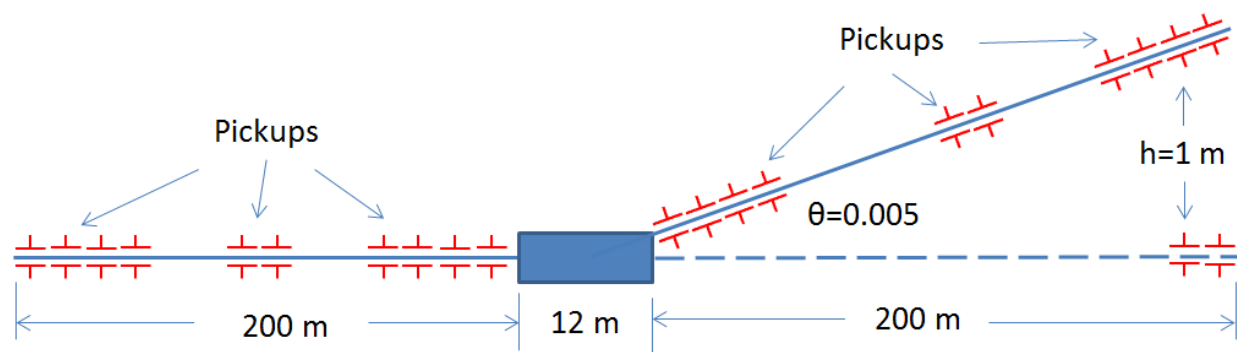


- Spectrometer measures the energy of the extracted beam. Advantage: much larger bending field can be applied to deflect a beam compared to the regular arc magnets.
- To get the required energy resolution in the order of  $10^{-6}$ , the sensitivity of pickups should be in the order of 1 micron, if a beam is deflected in the end of a channel by  $h=1 \text{ m}$ .
- 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:  $\frac{\Delta E}{E} = \frac{\Delta(Bl)}{Bl} - \frac{\Delta h}{h} \approx 10^{-6}$

- To get the required  $\Delta h=1$  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).



- 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 Earth's field.

- 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.

# 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:  $\chi < 1.8$  ( $\chi = v_0 \sigma_\delta / v_s$ ), otherwise it will happen fast decoherence of the spin precession. This led to operation of the collider with high value of the synchrotron tune:  $v_s > 0.1$  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.