Energy calibration issues in electron-positron Higgs factories

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Outline

- Introduction.
- Resonant depolarization technique – base line scenario.
- Alternative approach: observation of coherent precession of spins of polarized beams accelerated top up in a linac and in a booster ring.
- Longitudinal Compton Backscattering Polarimeter.
- Magnetic spectrometer based on ultra-sensitive BPMs.
- Conclusion.

Opportunities in EW precision physics

Observable	Measurement	Current precision	TLEP stat.	Possible syst.	Challenge
m_Z (MeV)	Lineshape	91187.5 ± 2.1	0.005	< 0.1	QED corr.
Γ_Z (MeV)	Lineshape	2495.2 ± 2.3	0.008	< 0.1	QED corr.
R_l	Peak	20.767 ± 0.025	0.0001	< 0.001	Statistics
R_b	Peak	0.21629 ± 0.00066	0.000003	< 0.00006	$g \rightarrow bb$
N_ν	Peak	2.984 ± 0.008	0.00004	< 0.004	Lumi meas.
$\alpha_s(m_Z)$	R_l	0.1190 ± 0.0025	0.00001	0.0001	New Physics
m_W (MeV)	Threshold scan	80385 ± 15	0.3	< 0.5	QED Corr.
N_ν	Radiative returns $e^+e^- \rightarrow \gamma Z, Z \rightarrow \nu\nu, ll$	2.92 ± 0.05 2.984 ± 0.008	0.001	< 0.001	?
$\alpha_s(m_W)$	$B_{had} = (\Gamma_{had}/\Gamma_{tot})_W$	B_{had} = 67.41 ± 0.27	0.00018	< 0.0001	CKM Matrix
m_{top} (MeV)	Threshold scan	173200 ± 900	10	10	QCD (~40 MeV)
Γ_{top} (MeV)	Threshold scan	?	12	?	$\alpha_s(m_Z)$
λ_{top}	Threshold scan	μ = 2.5 ± 1.05	13%	?	$\alpha_s(m_Z)$

M. Koratzinos, Washington, 25/3/2015

Introduction

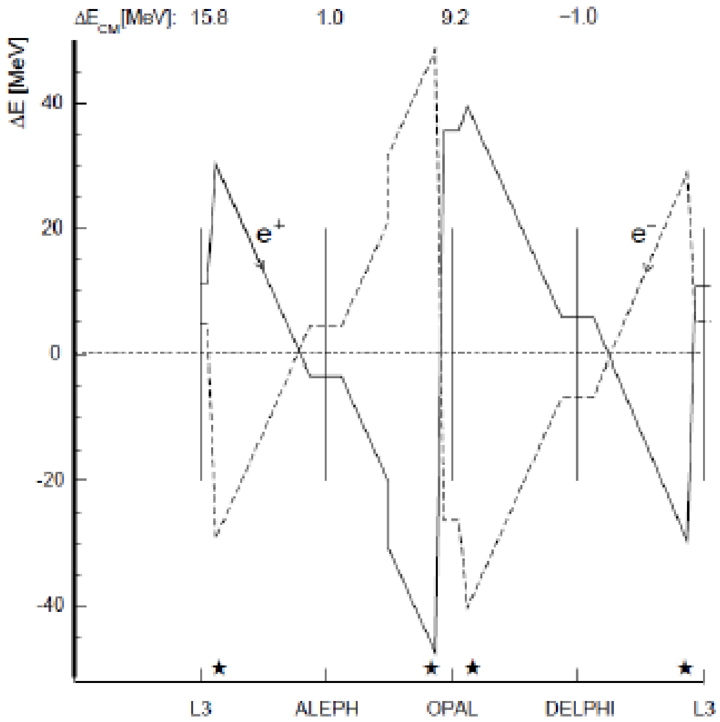
- FCC-ee and CEPC need 50 keV beam energy resolution at Z and 100 keV at W, separately in both rings.
- Only the Resonant Depolarization (RD) can provide such extreme absolute accuracy: $\Delta E/E \sim 1 \cdot 10^{-6}$!
- RD measures averaged over the circumference energy.
- But a local energy differs from the average one according to saw tooth phenomena (SR losses + energy gain from RF).

- SR losses per turn: 30 MeV at Z and 330 MeV at W.
- Longitudinal impedance distribution along the circumference also contributes to saw tooth picture, still could be accounted via extrapolation of energy measurements to zero beam current.

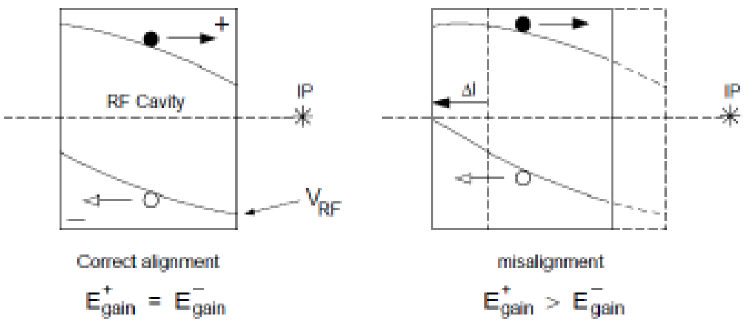
Introduction, cont.

- So, in principle, we shall pay efforts to develop the local energy monitors, almost as sensitive as RD.
- These monitors (magnetic spectrometers) will be tested and calibrated (absolutely) via RD at low energies, say at 20 - 30 GeV, where SR is rather low, ΔE_{turn}= 1.1 - 5.7 MeV, respectively.
- To extend their calibration to higher energies we shall rely on thorough field map studies in a lab.
- Magnetic spectrometers will provide beam energy calibration and control at energies beyond the limit for RD technique: say above 100 GeV per beam.

RF corrections



Errors arise due to cavity misalignments primarily:



- At LEP cavity misalignment was assumed to be 1.4mm in 1995

Work is needed to reduce this error. For LEP the error was of the order of 500keV (leading to an error of 400/200keV for the mass/width of the Z. Need to reduce this error by (more than) a factor of 10!

This might be the dominant error at FCC-ee

Review of polarization scenarios.

Two main scenarios are currently under discussion:

1) Start operation with injection of about 250 non-colliding bunches. Switch on asymmetric wigglers making the ST polarization time at Z-pole $\tau \approx 12$-25 hours and polarize beam to 10% polarization level (during 1 hour). Switch off wigglers and start normal run. Depolarize every 6 min one bunch.

2) Alternative: continuously prepare polarized bunches at 1 GeV damping ring (70-90% polarization level) using strong asymmetric wigglers to decrease polarization time to few minutes. Then accelerate beams top up in a sequence of synchrotrons preserving polarization by the use of Siberian Snakes. Inject beams with polarization rotated into the horizontal plane. Measure a free spin precession frequency using the longitudinal Compton polarimeter.

Resonant depolarization scenario, as a base line.

- Well established technique since 70-th (ϕ, ω, K-meson masses at VEPP-2M; J/ψ, ψ', D, ϒ at VEPP-4 and VEPP-4M; Z at LEP).
- Still large energy spread $\sigma_\delta > 0.001$ will limit the self-polarization approach at energies above 80 GeV, when $\sigma_\delta \cdot \nu_0 \geq 0.2$ ($\nu_0 = \gamma a = 180$).
- Also the self-polarization time is too large, exceeding 250 h at Z pole. Therefore shall think on other possibilities.
- Polarization wigglers, like used at LEP, switched on for 1 hour, to polarize few hundreds of bunches to 5%-10% polarization level, may solve a problem for Z and W, but not for full energy range.
- Then, other energy monitors shall be calibrated by RD and will be used for continuous energy monitoring, as requested by physics.

Sokolov-Ternov build-up rates (E. Gianfelice talk, Washington)

- High precision beam energy measurement ($\ll 100$ keV) is needed for Z pole physics at 90 GeV CM energy and W physics at 160 CM energy. RF depolarization widely used at LEP it can provide a $\sim 10^{-6}$ accuracy.
- Z pole physics would profit from longitudinal beam polarization.

Sokolov-Ternov polarization build-up rate

$$\tau_p^{-1} = \frac{5\sqrt{3}}{8}\frac{r_e \gamma^5 \hbar}{m_0 C}\oint \frac{ds}{|\rho|^3}$$

for FCC-ee with $\rho \simeq 10424$ m

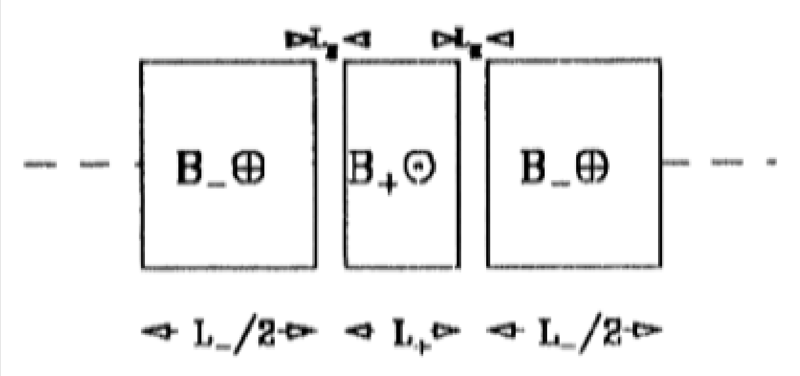
E (GeV)	U_0 (MeV)	$\Delta E/E$ (%)	τ_{pol} (h)
45	35	0.038	256
80	349	0.067	14

Asymmetric field wiggler (E. Gianfelice talk)

For decreasing the polarization time keeping the polarization level high wigglers are introduced in the lattice. Constraints:

- $x' = 0$ outside the wiggler $\Rightarrow \int_{wig} ds\, B_w = 0$ (vanishing field integral)
- $x = 0$ outside the wiggler $\Rightarrow \int_{wig} ds\, sB_w = 0$ (true for symmetric field)
- P large $\Rightarrow \int_{wig} ds\, B_w^3$ must be large

LEP polarization wiggler



$$\int_{wig} ds \frac{1}{\rho_w^3} = \frac{L_+}{\rho_+^3}\left(1 - \frac{1}{N^2}\right) \qquad N \equiv L_-/L_+ = B_+/B_-$$

N should be large for keeping polarization high!

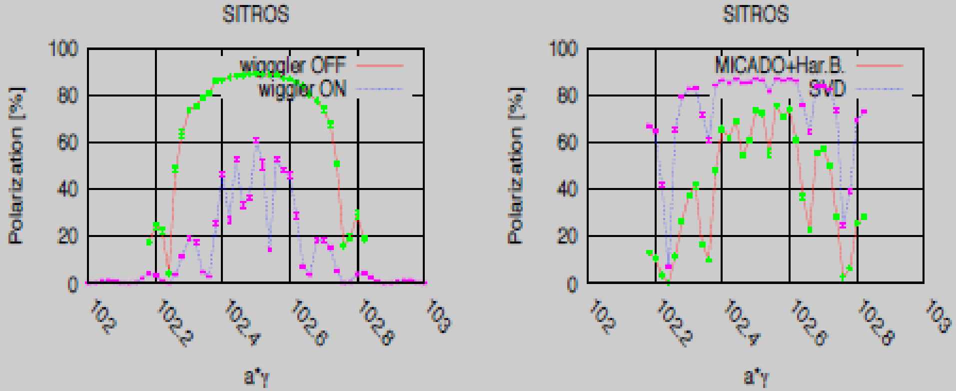
Spin resonances compensation (E. Gianfelice talk)

1 wiggler with B_+=1.35 T for reaching 10% polarization (enough for energy calibration) after 140'.

"toy" ring

- 200 μm quadrupole misalignment
- 1 corrector + 1 BPM close to each vertical focusing quad
- correction
  - MICADO like correction + *harmonic bumps*

    or
  - use of all BPMs and correctors through SVD analysis



Beam parameters scaling upon a wiggler field value

E=45 GeV, arc bends radius ρ_0 =10.4 km, l_1=1.3 m, l_2=l_1·N=7.8 m				
B (T)	τ_p (hours)	P_∞ (%)	$(\sigma_\delta)_{SR}$, σ_E (MeV)	U_0 (MeV)
0	256	92.4	0.000378, 17	34.9
1.1	25.4	87.9	0.001125, 50.6	39.6
1.3	16	87.7	0.001384, 62	41.4
2.6	2.1	87.4	0.003134, 141	61.1

$$\tau_p^{-1} = \frac{5\sqrt{3}}{8} \lambda\!\!\!^{-}_e r_e c \gamma^5 \left\langle \frac{1}{|\rho|^3} \right\rangle = \tau_0^{-1} \frac{B_0^3 l_0 + |B_1^3| l_1 + |B_2^3| l_2}{B_0^3 l_0}$$

$$(\sigma_\delta)^2_{SR} = \frac{55\sqrt{3}}{192} \frac{\lambda\!\!\!^{-}_e}{B\rho} \gamma^2 \frac{B_0^3 l_0 + |B_1^3| l_1 + |B_2^3| l_2}{B_0^2 l_0 + B_1^2 l_1 + B_2^2 l_2} \qquad \Delta E_{turn} = \frac{2}{3} mc^2 r_e \gamma^4 \frac{B_0^2 l_0 + B_1^2 l_1 + B_2^2 l_2}{(B\rho)^2}$$

Correlation of energy spread with the self-polarization level

In a given machine (LEP) was studied using the damping wigglers.

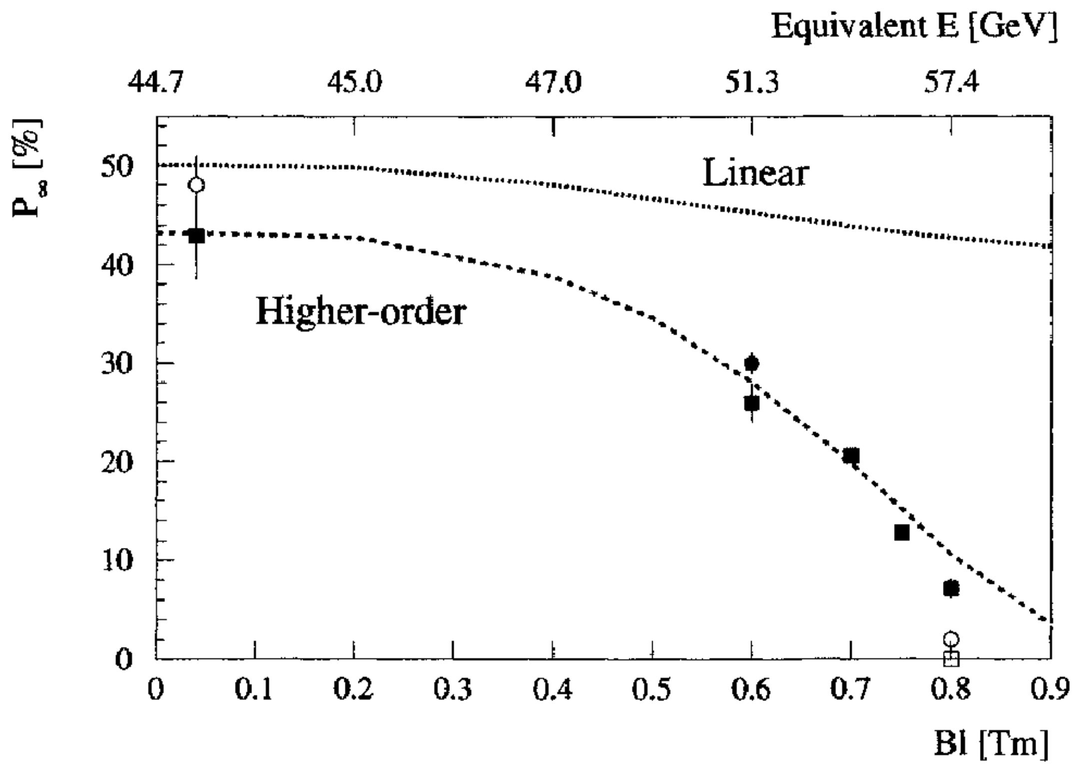
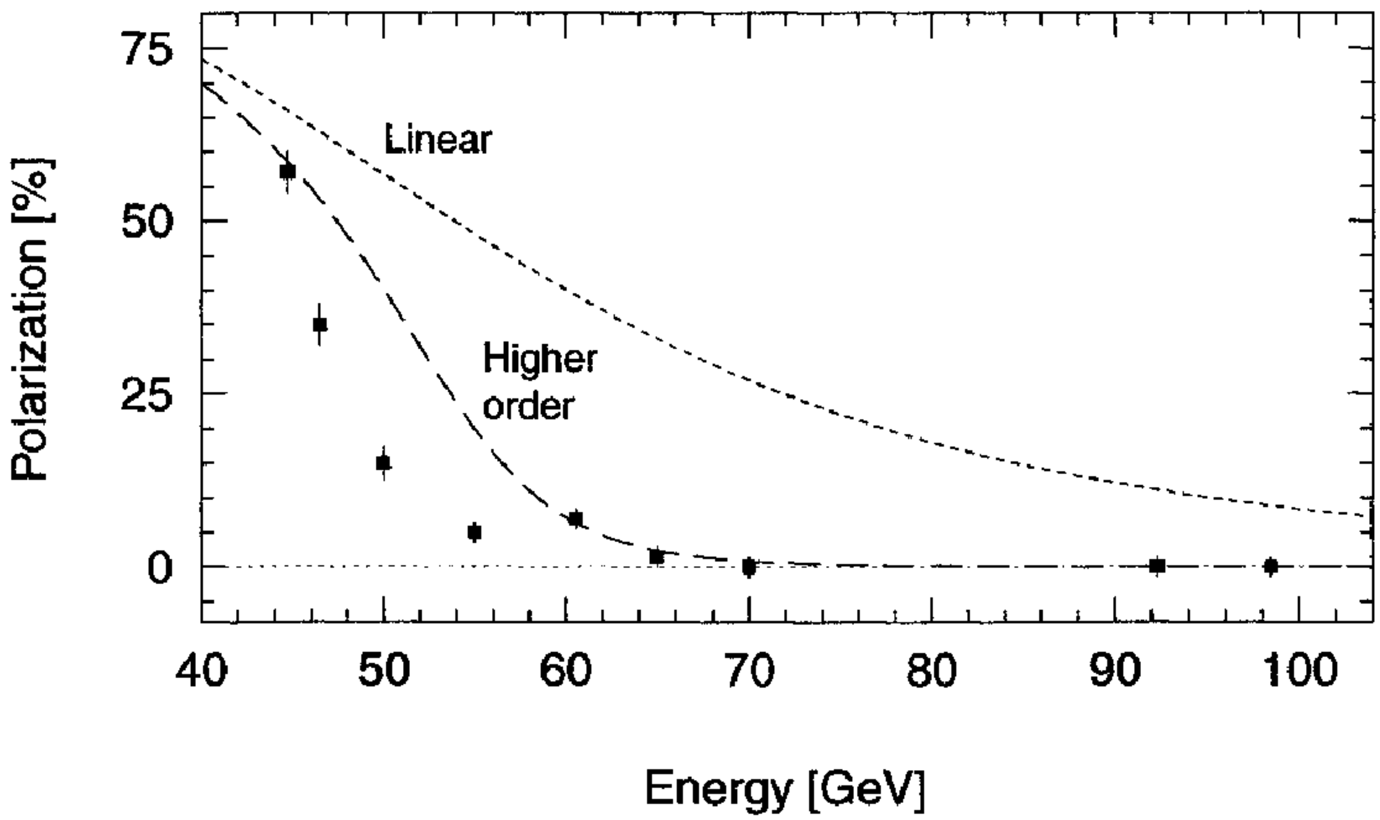


FIGURE 8. Observed polarization level at 44.7 GeV for different excitations Bl of the LEP damping wigglers. The upper scale indicates the beam energy that would produce the same spin tune spread. The polarization measurements are compared to the expectations from linear and higher-order theory.

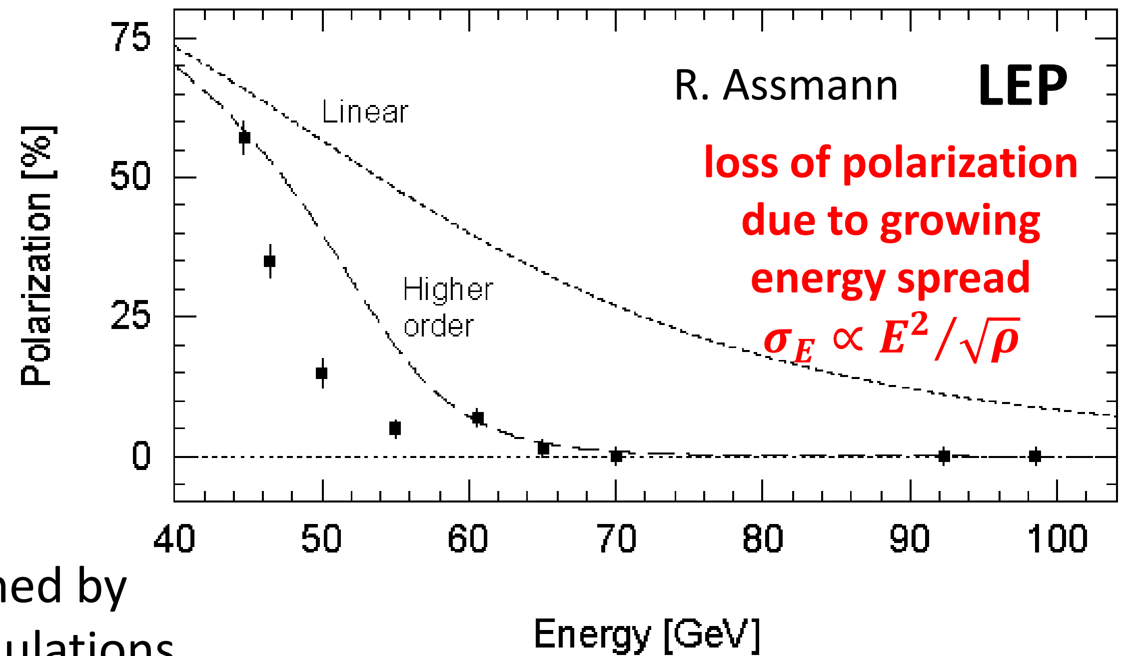
Alain Blondel, TLEP polarization 2013-10-17

$$\sigma_E \propto E_b^2 / \sqrt{\rho}$$

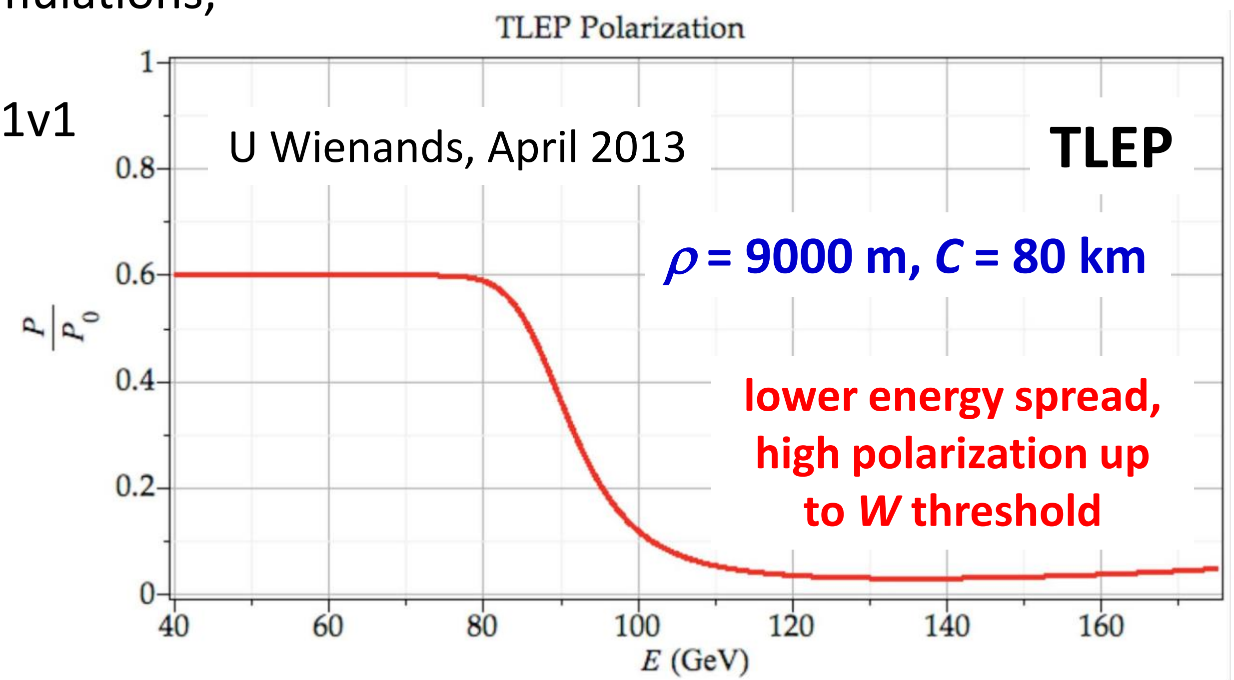


The good news is that polarization in LEP at 61 GeV corresponds to polarization in TLEP at 81 GeV

➔ Good news for M_W measurement



This was confirmed by higher order simulations, S.R.Mane, arXiv:1406.0561v1



Alain Blondel, TLEP polarization 2013-10-17

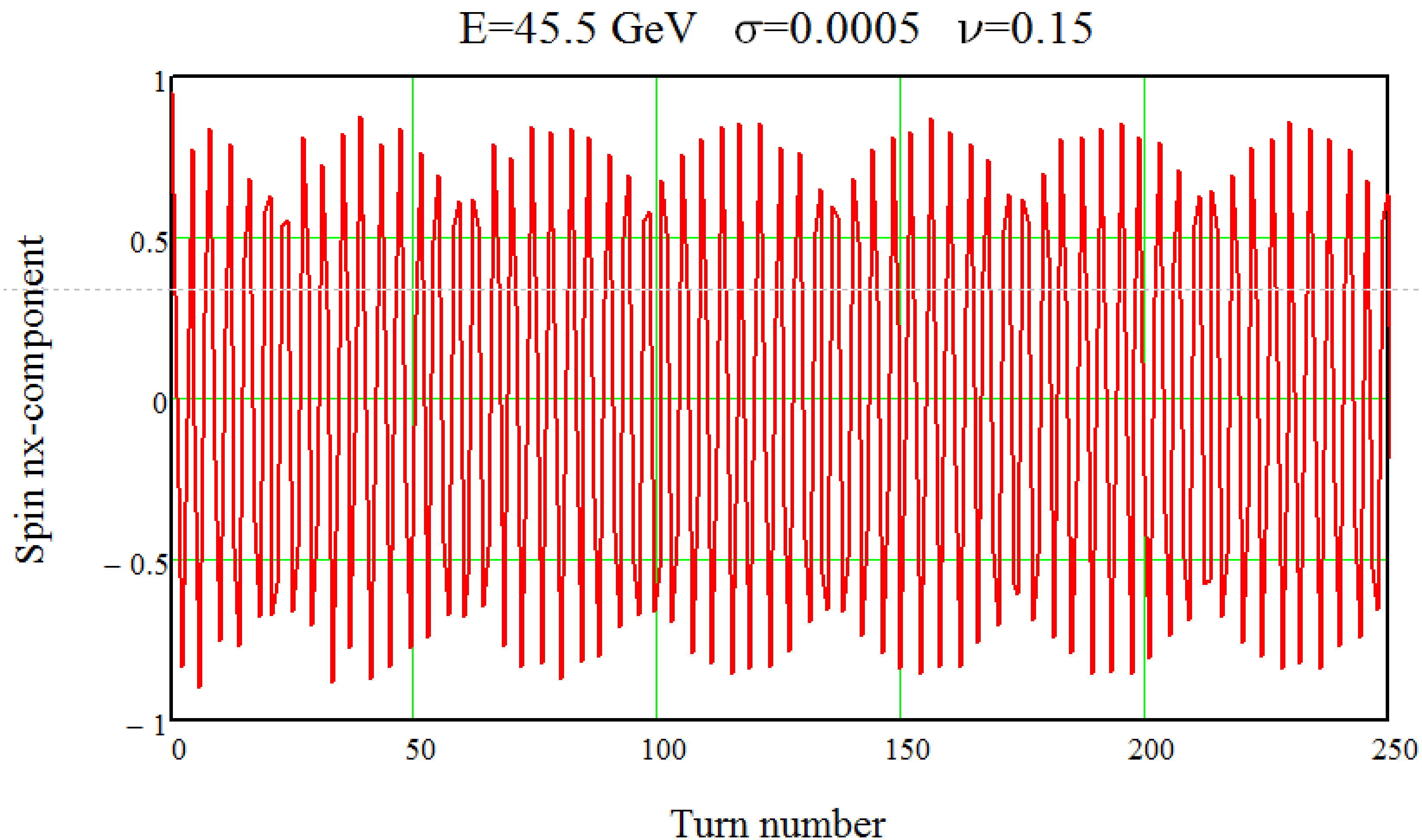
Free precession concept - advanced scenario

1. Production of polarized e+ in damping ring at 1 GeV, achieving polarization time 2 - 5 min (by use of high field bends or wigglers).
2. Production of polarized electrons from a laser photocathode, or in a damping ring for the energy calibration only, like e+.
3. Acceleration of polarized beams via linac and finally in the 100 km booster storage ring, preserving there polarization by the help of Siberian Snakes (solenoid-type spin rotators).
4. Injection of polarized bunches into the collider rings with the horizontal spin orientation and measuring turn by turn the free precession frequency using the longitudinal Compton polarimeter.
5. The number of polarimeters should be large (≥4). Then one can measure the spin precession phase advances per every arc sector. This paves a way to validate the saw-tooth energy distribution model, constructed on the full data set, such as RF-voltage and RF-phases, plus orbit data from BPMs, plus geodesy data, plus many other data.

Free precession concept, cont.

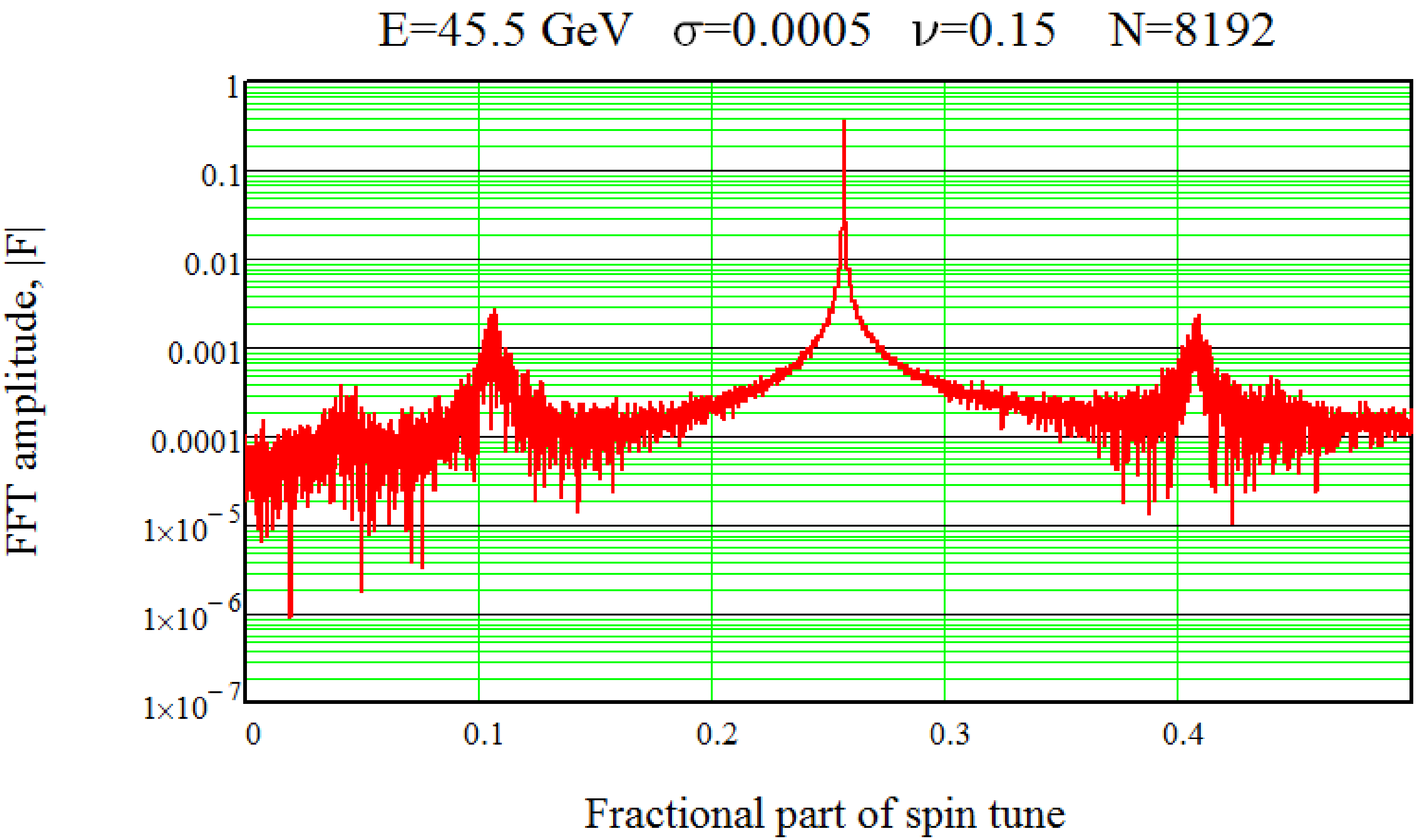
6. Shall measure beam energy using the magnetic spectrometers or other type local energy monitors (in several points, about 4).
7. Absolute calibration of any spectrometric system will be done by a measurement of the spin precession frequency at low energy, say about 20 - 30 GeV, where SR is weak and can be accounted with very good accuracy. Measurement of the spin precession phase advances shall provide a cross-check of this calibration.
8. Dephasing of spins in coherent precession depends strongly on synchrotron modulation index: $\chi = \sigma_\delta \nu_0/\nu_s$ ($\nu_0=\gamma a$). It should be chosen not too large: acceptable is $\chi < 1.7$ ($\nu_s >$ 0.1 - 0.2).
9. Resonance depolarization method is not excluded, but did not work near integer resonances and above 80-100 GeV. In contrast, the free precession method works everywhere!
10. Shall measure, suppress and account spin resonances in some energy interval near the energy of interest, because the spin resonances can modify the spin tune in their vicinity.

Spin tracking oscillogram. 125 test-particles.
E=45.5 GeV, σ_δ=0.0005, ν_s =0.15, τ_s =1320 turns



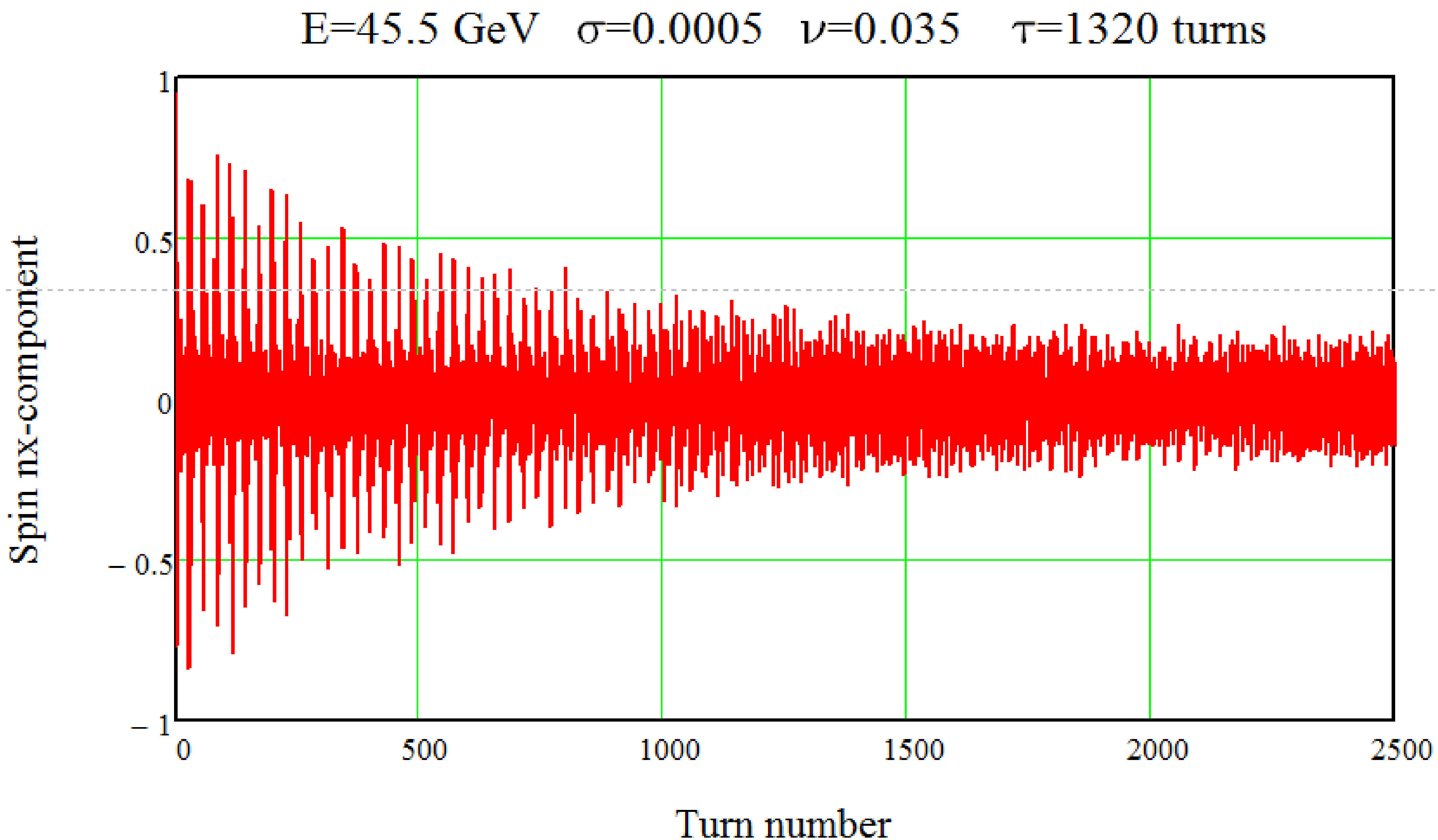
Loss of polarization degree due to de-phasing is small thanks to high enough ν_s.
Spin echo at synchrotron frequency are clearly visible!

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



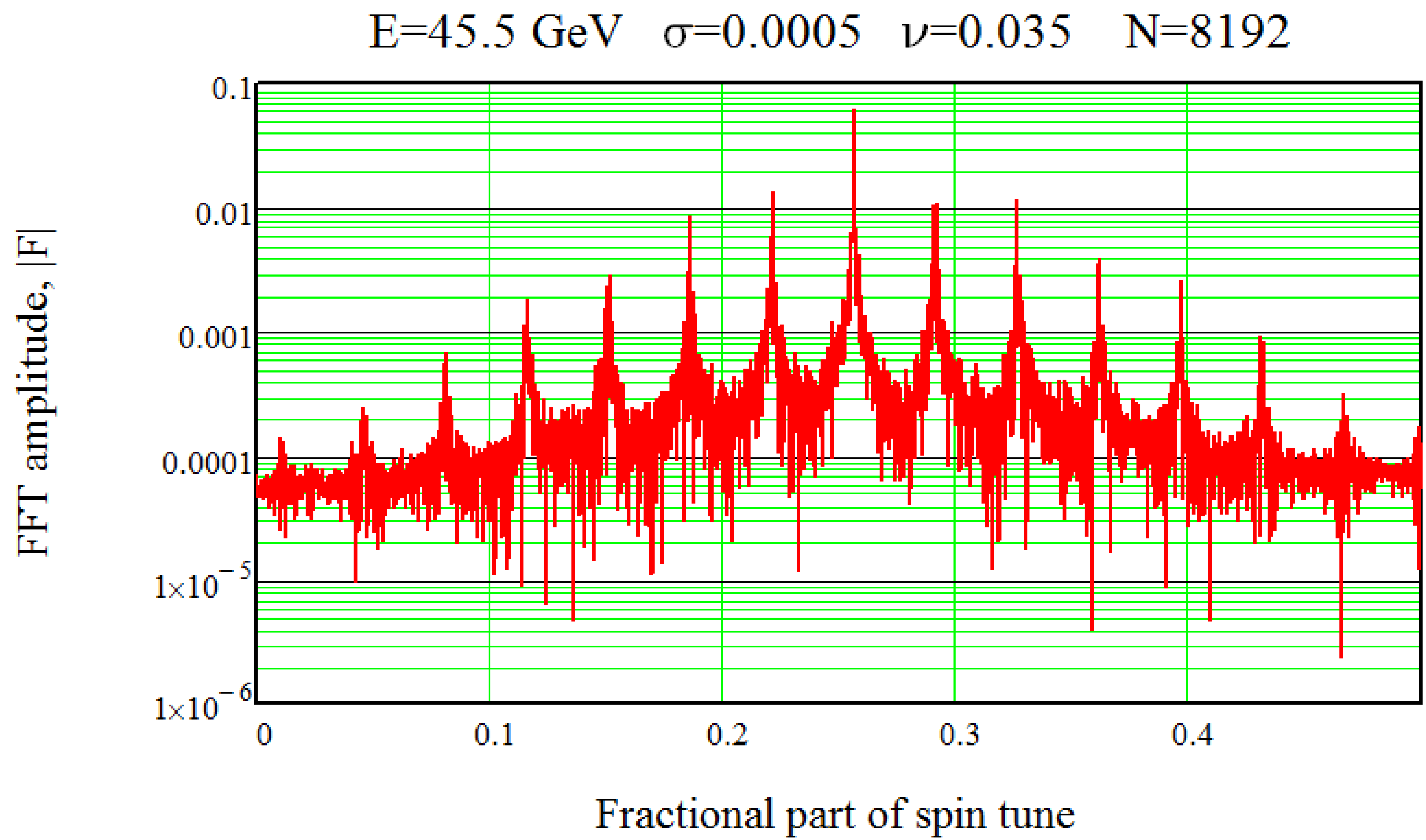
$\chi = \sigma_\delta \nu_0 / \nu_s = 0.35$ – synchrotron modulation index.

Spin tracking oscillogram. 125 test-particles.
E=45.5 GeV, σ_δ=0.0005, ν_s =0.035, τ_s =1320 turns



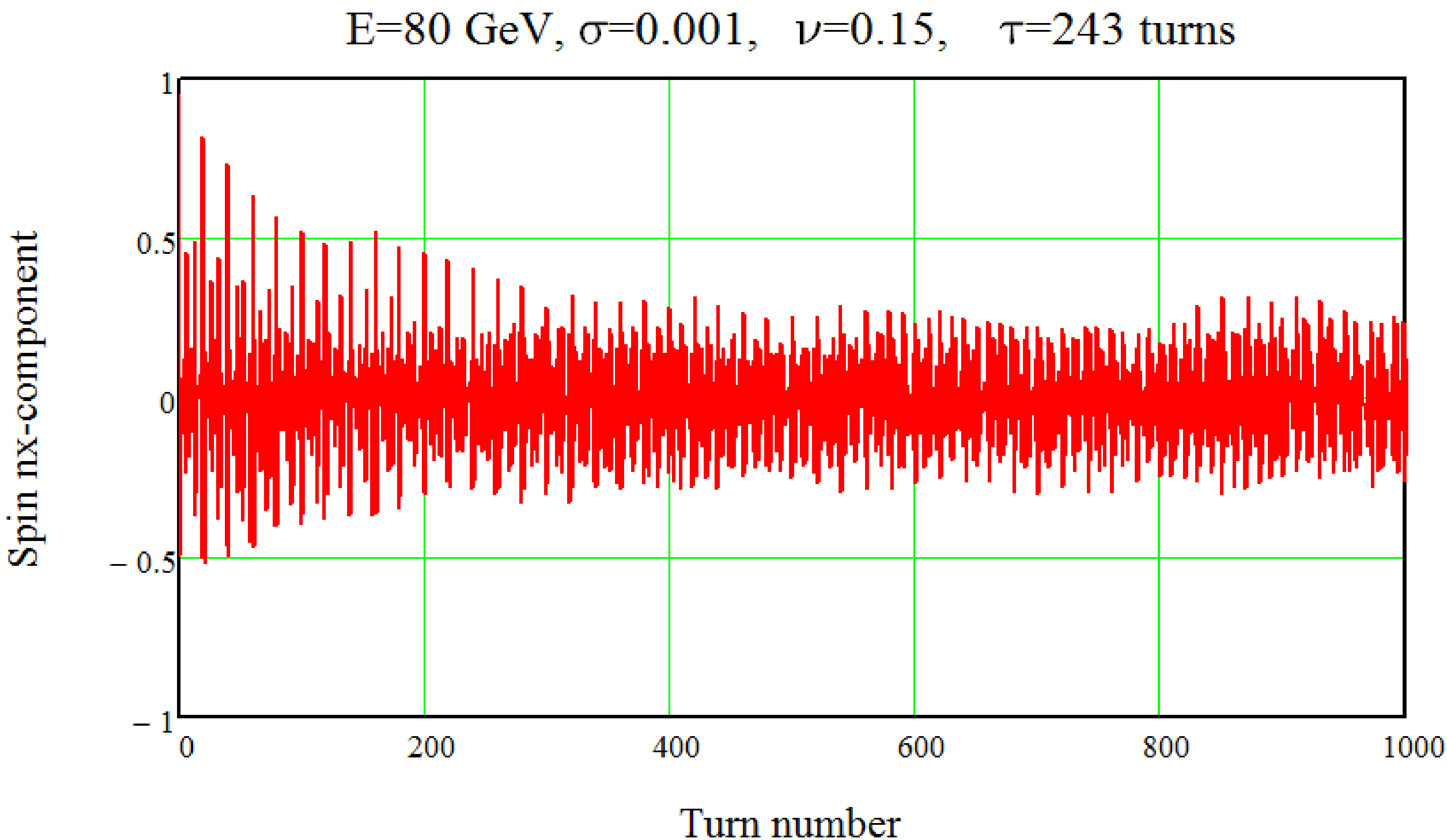
Spin precession spectrum. Number of turns 8192.

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



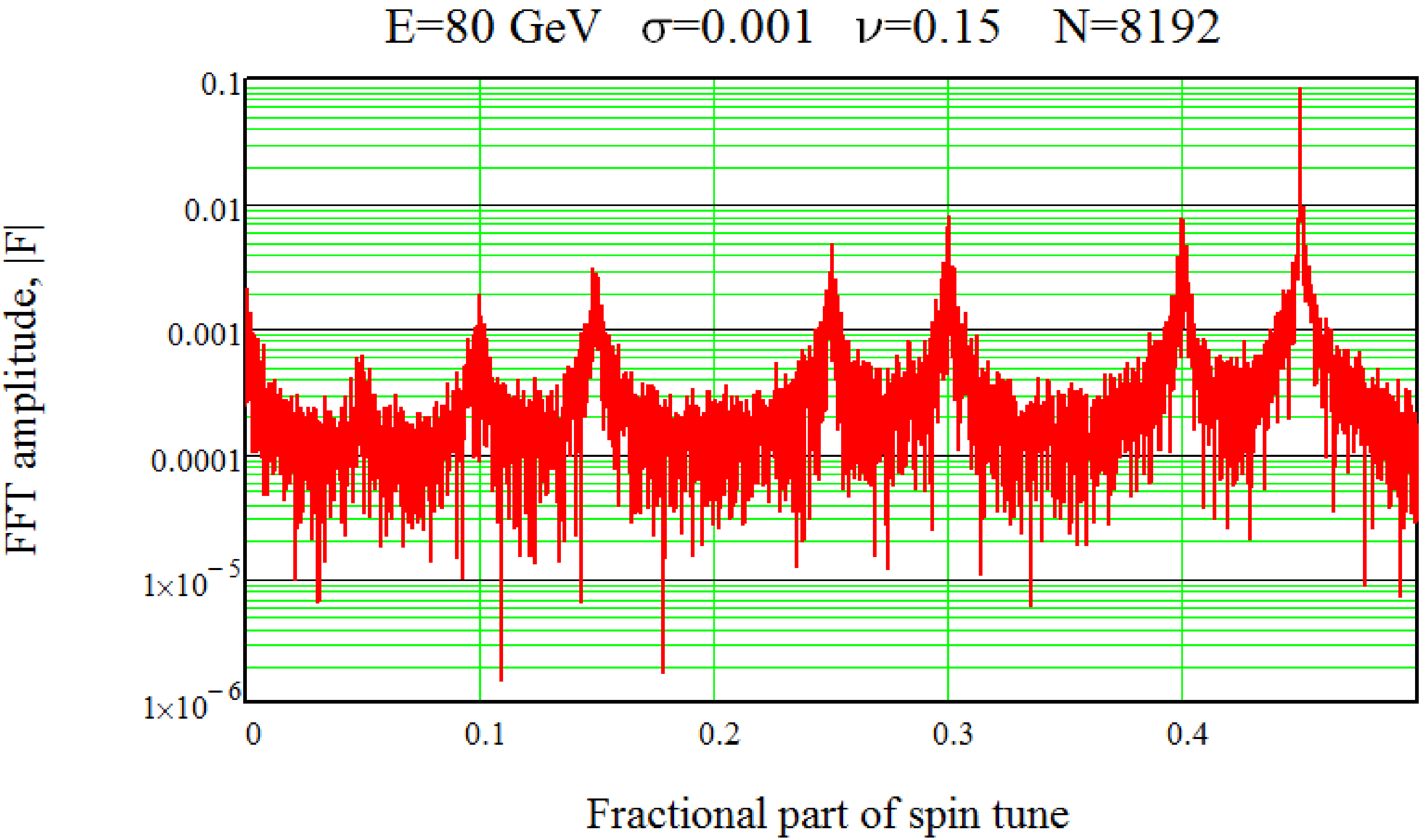
We want: $\chi < 1.7$. With $\chi > 1.7$ peaks disappear!

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

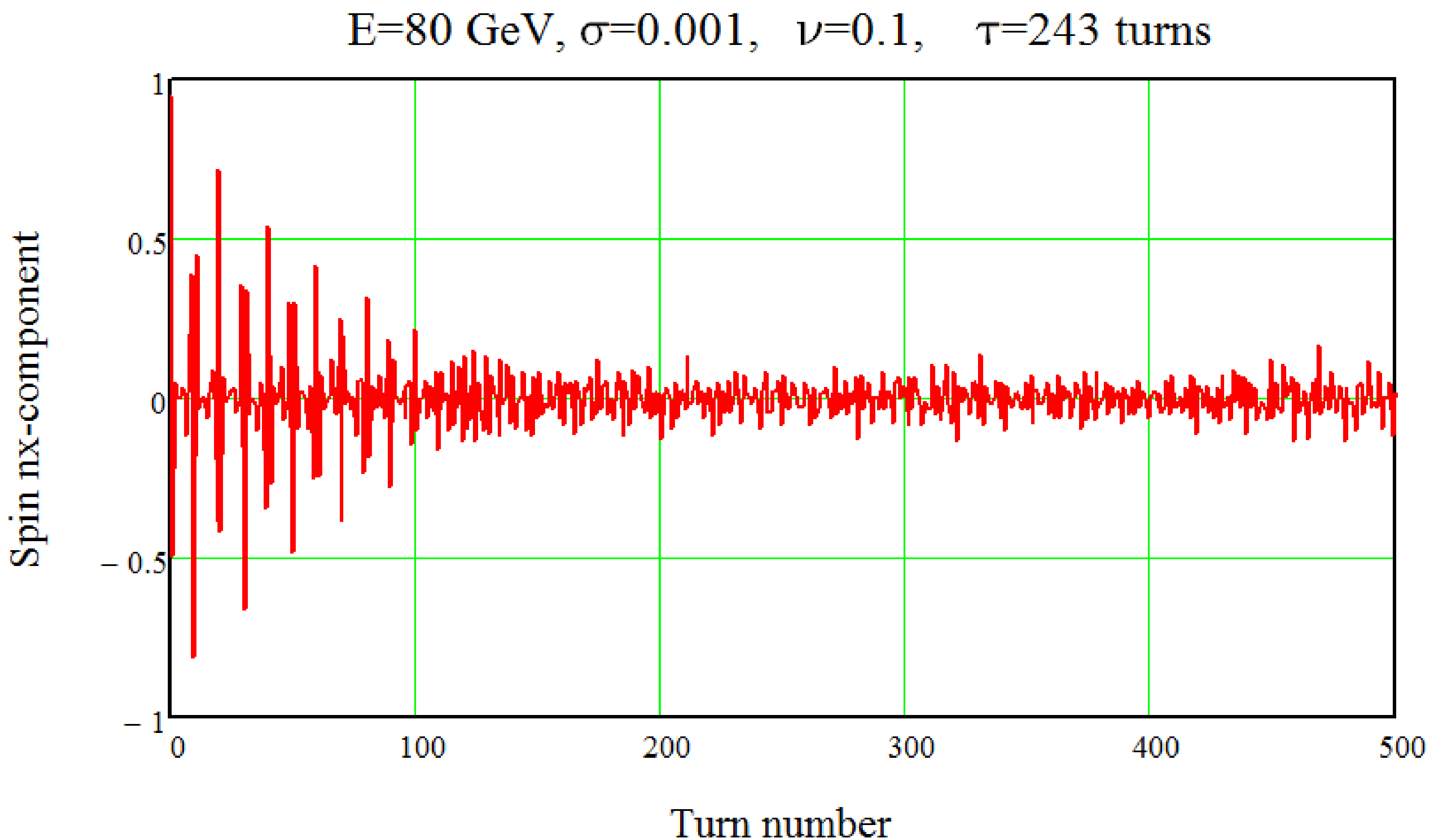


Spin precession spectrum. Number of turns 8192.

E=80 GeV, ν_0=181.55, σ_δ=0.001, ν_s =0.15, χ=1.21

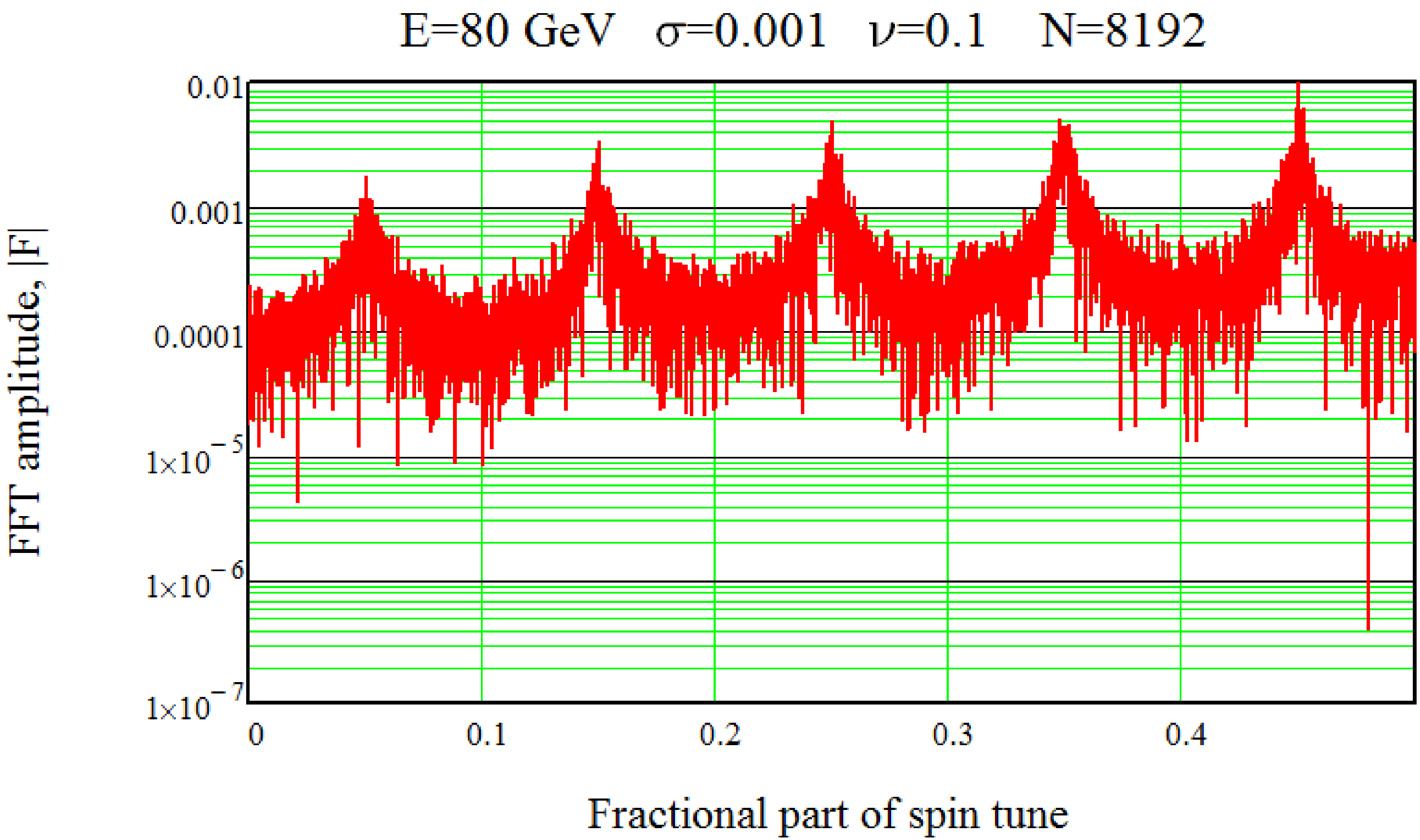


Spin tracking oscillogram. 125 test-particles. E=80 GeV, σ_δ=0.001, ν_s =0.10, τ_s =243 turns



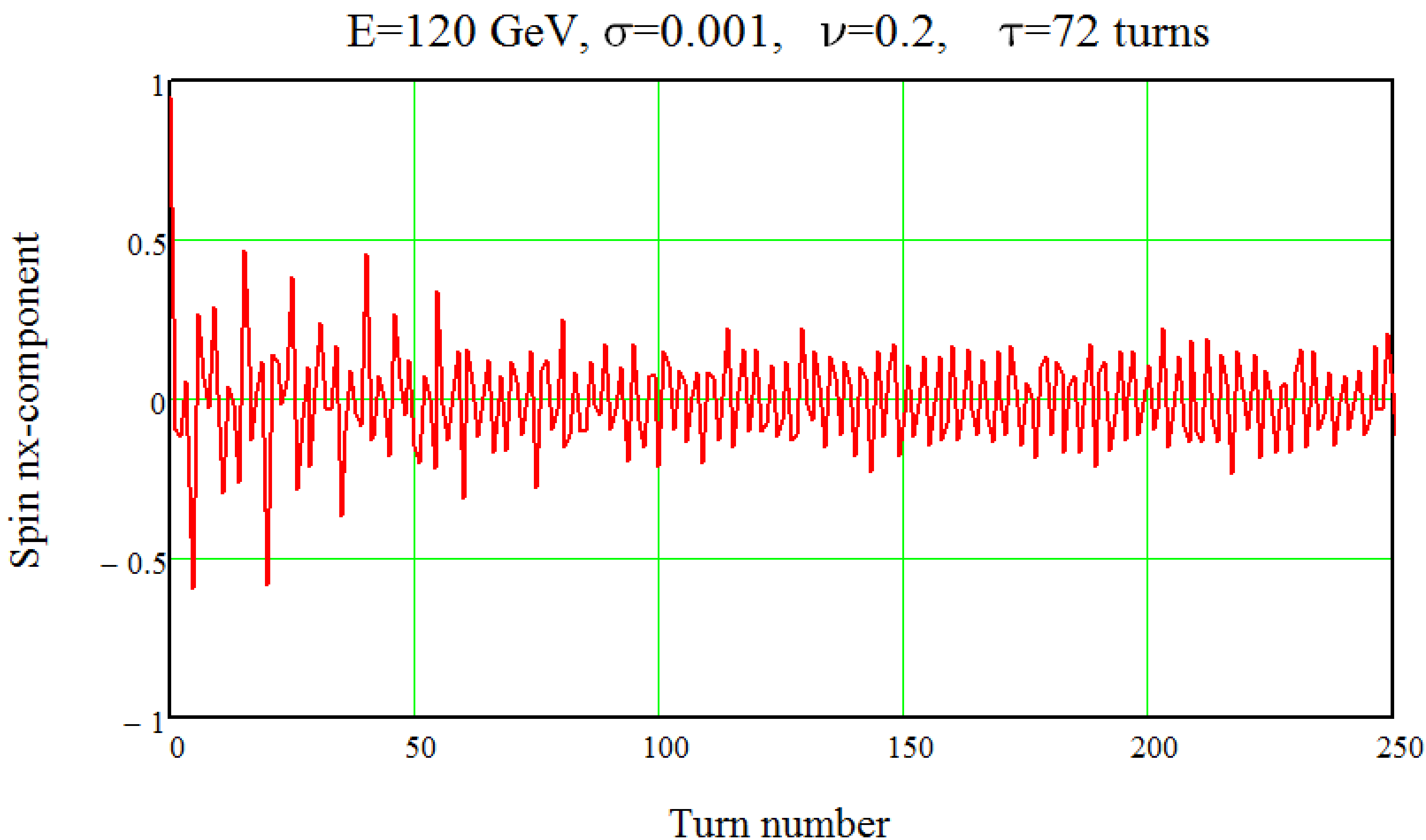
Fast de-phasing due to slow synchrotron motion!

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



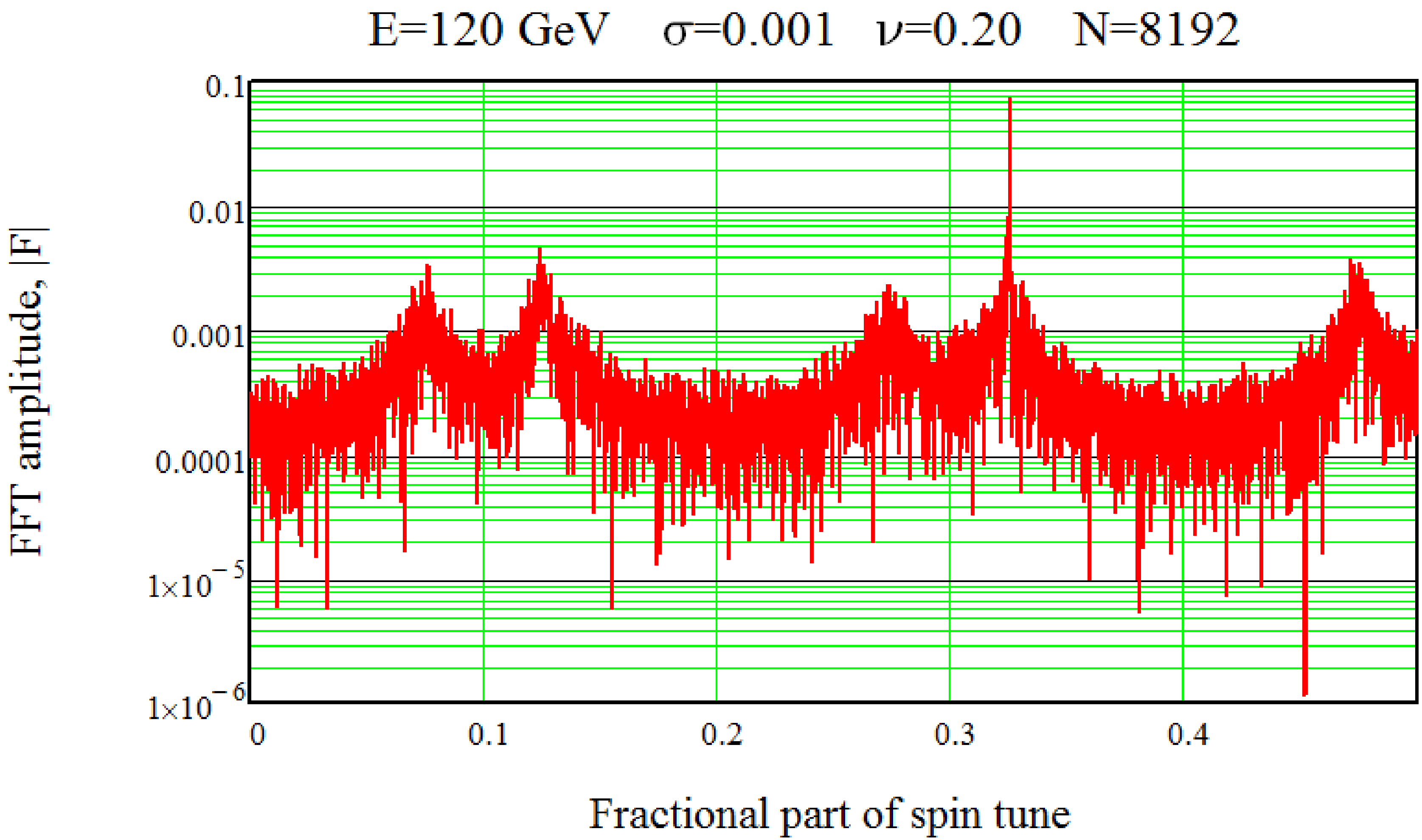
Same results one gets with doubled both: energy spread and synchrotron tune.

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



Fast dephasing! Synchrotron modulation index is too high: χ=1.36.

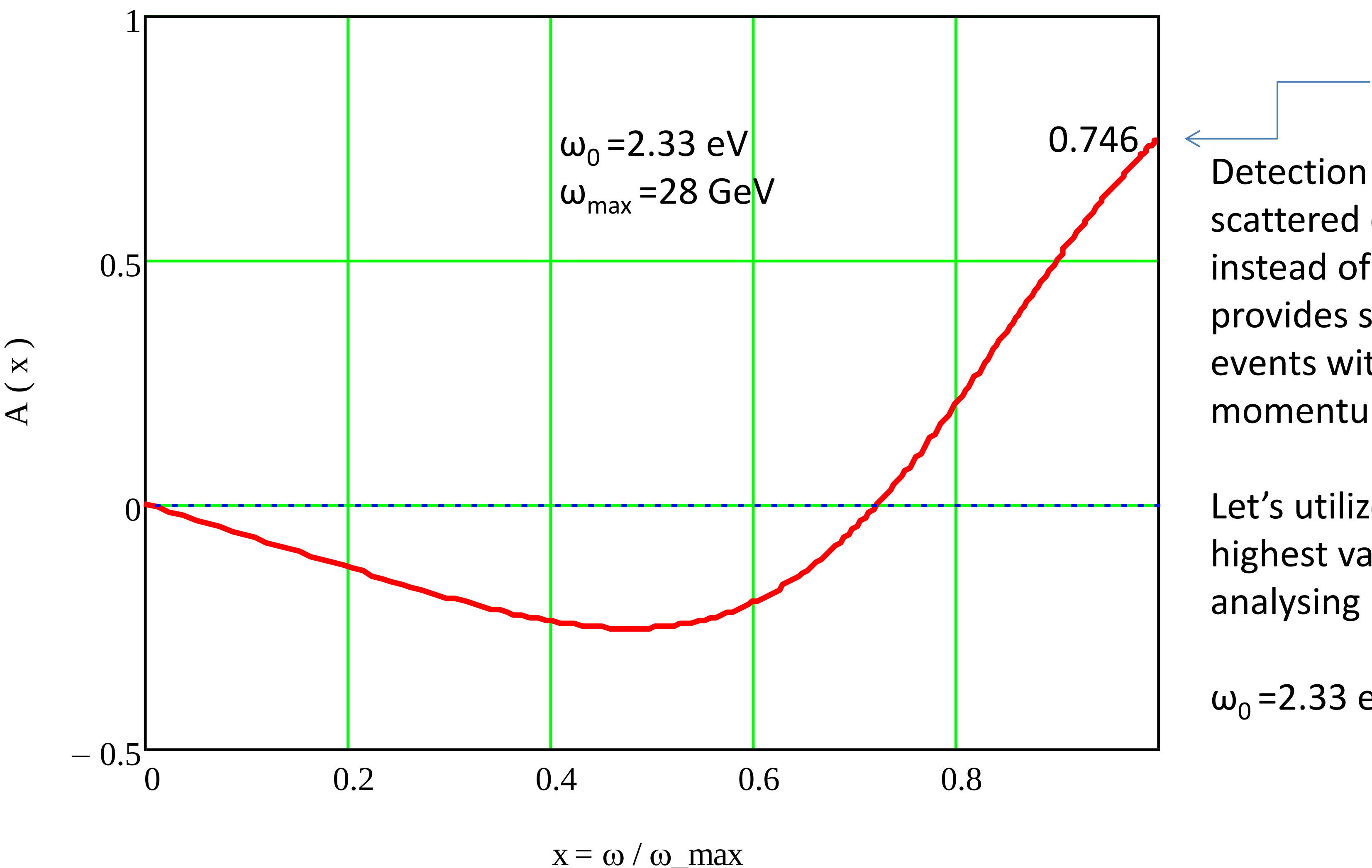
Spin precession spectrum. Number of turns 8192. E=120 GeV, ν_0=272.325, σ_δ=0.001, ν_s =0.20, χ=1.36



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

Longitudinal polarimeter based on Compton scattering of a laser light

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!

ω_0 =2.33 eV

Accuracy of spin precession measurements.

Normalized signal: $U_k = \sin(\Omega k + \Psi) + \xi_k, \qquad k = 0,1,..,N-1$

With white Gaussian noise: $\langle \xi_k \rangle = 0, \quad \langle \xi_k{}^2 \rangle = \sigma^2$

Signal fitted by three parameters (A, ω, ψ): $u_k = A\sin(\omega k + \psi)$

Least squares minimization of χ^2 :

$$\chi^2 = \frac{1}{2}\sum_{k=0}^{N-1}\left(u_k - U_k\right)^2 = \frac{1}{2}\sum_{k=0}^{N-1}\left(A\sin(\omega k + \psi) - \sin(\Omega k + \Psi) - \xi_k\right)^2$$

Best fit estimator error bar sigma:

$$\sigma_A{}^2 = \frac{2\sigma^2}{N}, \qquad \sigma_\psi{}^2 = \frac{8\sigma^2}{N}, \qquad \sigma_\omega{}^2 = \frac{24\sigma^2}{N^3}$$

Let: $N = 3\cdot 10^4$ and $\sigma = 2.5$, then:

$$\sigma_\nu = \frac{\sigma_\omega}{2\pi} = \frac{\sqrt{24}\cdot 2.5}{2\pi\cdot(3\cdot 10^4)^{3/2}} \simeq 3.75\cdot 10^{-7}$$ - much below wanted $1\cdot 10^{-4}$ (ν=100 !)

Accuracy of spin precession measurements, cont.

Semi-optimistic estimation of energy spread due to spread of amplitudes of synchrotron oscillations about average energy $\langle\delta\rangle$:

$$\sigma_{\langle\delta\rangle} \approx \sigma_{\delta}{}^{2}$$

Spin tune spead estimation for beam energy 45 GeV ($\nu_0 \approx 100$):

$$\sigma_{\langle\nu\rangle} = \nu_0 \sigma_{\langle\delta\rangle} \approx 100 \cdot (4 \cdot 10^{-4})^2 = 1.6 \cdot 10^{-5},$$

$N \cdot \sigma_{\langle\nu\rangle} \cdot 2\pi < \pi \quad \rightarrow \quad N < (2\sigma_{\langle\nu\rangle})^{-1} = 3 \cdot 10^4$ - Limit to N due decoherence

$\sigma_{\psi} = \dfrac{\sqrt{8} \cdot 2.5}{\sqrt{3 \cdot 10^4}} = 0.04 \; rad$ - not very small! (wanted value $\sim 2 \cdot 10^{-4}$)

But could be reduced by factor of 100, for instance, via collecting data of 10000 beams injections.

Most important: it doesn't contain systematics!

Spin tune spread estimations

I. Koop and Yu.Shatunov, “The spin precession tune spread in the storage rings”,

in proceedings of EPAC88, p.738-739.

$$\bar{\delta} \simeq \alpha^{-1}\left[\frac{\varepsilon_x}{R}\cdot\gamma\frac{\partial \nu_x}{\partial\gamma}+\frac{\sigma_\delta^2}{\nu_x^4}\right]$$ - averaged over the phases of betatron and synchrotron oscillations relative energy shift

(in the uniform focusing approximation!)

Assuming: $\gamma\frac{\partial \nu_x}{\partial \gamma} \simeq 1$, $\alpha \simeq 10^{-5}$, $R = 10^4 m$, $\varepsilon_x \simeq 10^{-9}$ m,

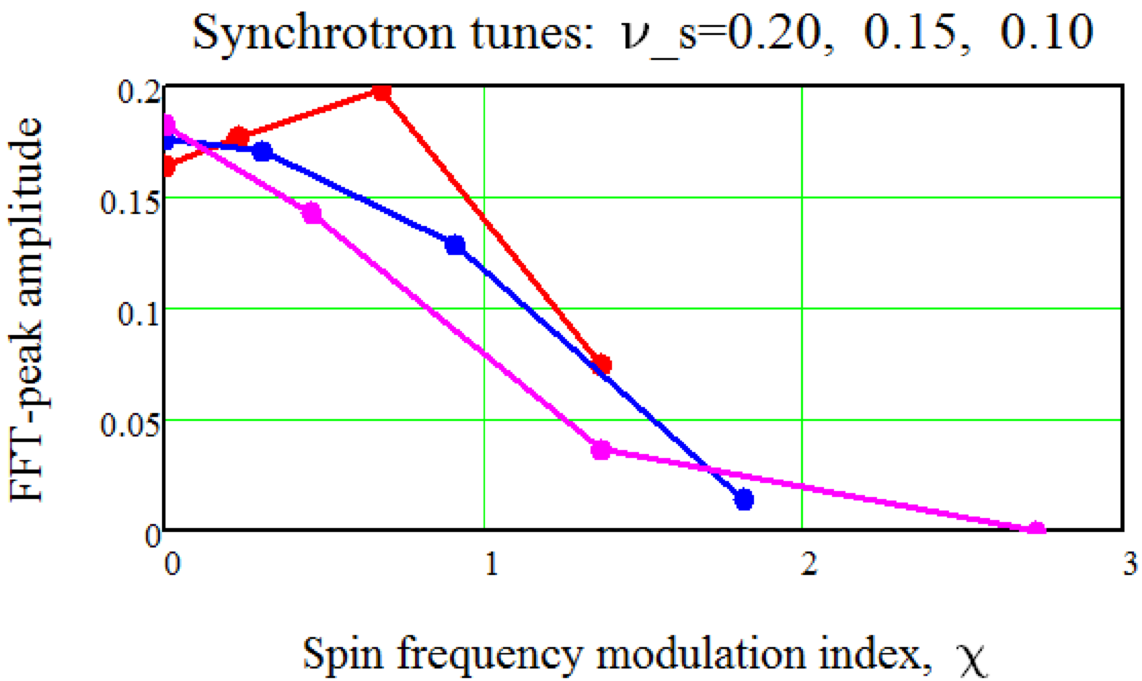
one gets for the betatron contribution $\bar{\delta} = 10^{-8}$, only!

This translates into 10^6 turns of the coherent spin precession (for ν=100)! Needs to be proved by simulations!

The synchrotron osc. term is less then $\bar{\delta} \le 10^{-11}$ (for $\nu_x \approx 433$).

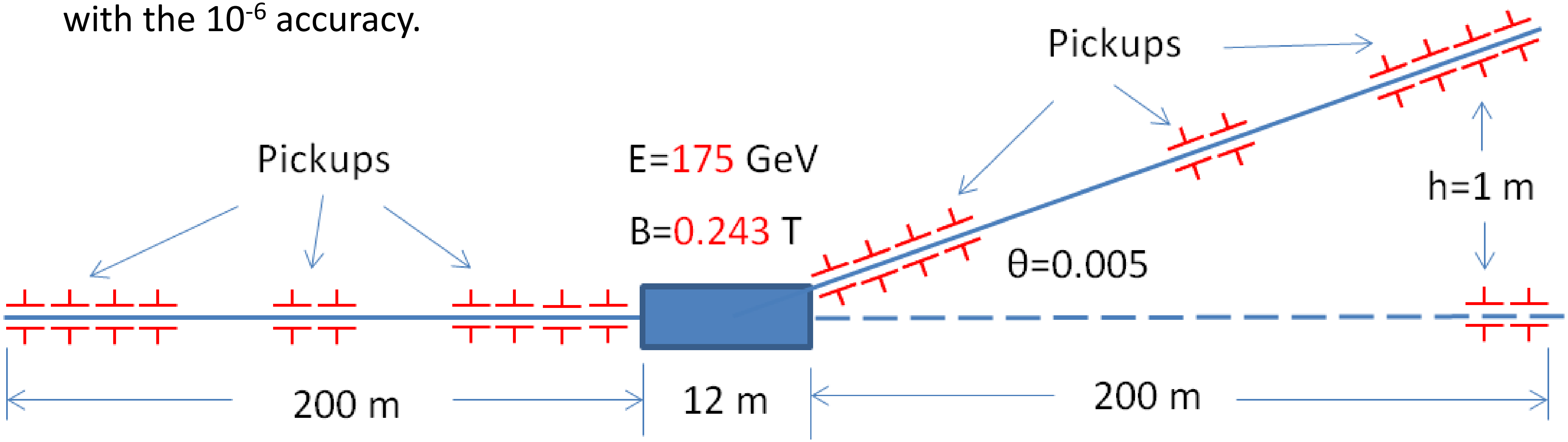
Discussion of Free Precession Option

- Spin de-phasing is governed by the synchrotron frequency modulation index χ. It should be low: $\chi < 1.7$, at least. So, large values of ν_s are preferable. Contrary to beam-beam optimization!?
- Spin tune spread also should be minimized to increase the spin coherent precession time to as much as possible.
- Seems, we shall perform special polarization runs with high ν_s and low *E* values, to calibrate all local magnetic spectrometers.



First thoughts on the magnetic spectrometer design

- Single bunch or short train of bunches are ejected from a ring into a long channel with the vertical bend and a set of pickups (need 1 micron sensitivity). These pickups are grouped in families of 4 - 10 units to provide a cross-check of beam position measurements in a group.
- Hydrostatic sensors, developed at BINP, can control the vertical location of pickups with the submicron resolution (A.Chupyra et al., FERMILAB-PUB-11-452-AD-APC-E).
- Invar wire or laser Interferometers shall continuously monitor all distances along the line with the 10^{-6} accuracy.



- Field integral in the dipole magnet needs to be measured to same accuracy by the electronic integrators and by a set of NMR probes.
- This magnet will be supplied with the special demagnetization coil to be able to reach very low residual fields. These residual fields shall be measured by the radio-optical methods with the needed sensitivity ($\approx 10^{-3}$ Gauss).

Discussion of the magnetic spectrometer option

- The extracted bunch energy measurement option is not as limited by the permissible bending radius, as in the ring spectrometer case.
- Ability to control the bending field integral with 10^{-6} accuracy shall be thoroughly studied in a lab.
- The vacuum chambers should be made from the non-magnetic material and well screened from the Earths field (at a level 10^{-3} Gs).
- The pickup electronics shall provide 10^{4} dynamic range (14-bit ADC).
- Absolute calibration of local energy monitors and study of different correlations of their outputs with the changes of environmental parameters (like temperatures, tides and so on) should be done at some sufficiently small beam energy E=20-30 GeV, where SR losses can easily be accounted with the required accuracy.
- Temporal stability of achieved absolute calibration of any type local energy monitors should be investigated very thoroughly during that low-energy regime studies!

Conclusion

- Polarization is the only tool to provide the absolute energy calibration with the required accuracy, approaching to 10^{-6} level.
- Polarization is also needed to calibrate the local energy monitors, such as a magnetic spectrometer, for instance.
- To receive the 10^{-6} relative beam energy resolution of that monitors looks quite challenging.
- A lot of R&D work should be foreseen to find the appropriate ways to solve this difficult task.