Polarization studies for beam parameters of CEPC and FCCee

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Outline

- Polarization specificity of CEPC and FCC-ee
- Simplified spin tracking code
- Attainable self-polarization degree estimations
- Resonant depolarization -
- Coherent free precession – two complementary techniques to determine the resonant spin precession frequency.
- Conclusion.

Polarization: CEPC and FCCee specificity

- Beam emittances in CEPC and FCCee are so small that all intrinsic resonances with betatron oscillation frequencies are suppressed and can be neglected:

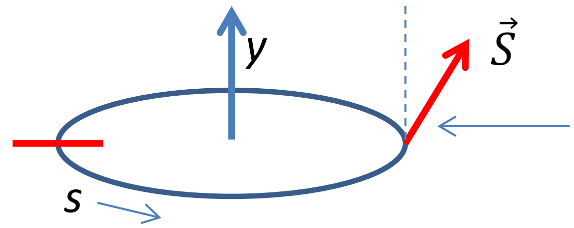
  $\nu_0 \cdot |\sigma_{y'}| \sim 2 \cdot 10^{-5}$ (even for E=80 GeV)

- Therefore, only static vertical orbit distortions and the longitudinal magnetic fields with nonzero integrals can affect the spin motion!

- Precession frequency modulation by the synchrotron oscillations is very important! The relevant parameter is: $\xi = \nu_0\, \sigma_\delta / Q_s$ Must prefer $\xi < 1$, means: Q_s is as high as possible! At LEP was Q_s=0.083 - comfortable for E=45 GeV!

Simplified spin tracking code

Spin perturbation, *w*
Is localized at *s*=0.
Random jumps of relative energy deviation δ are localized also here.



Spin precession around the *y*-axis with ν ~ δ.
Radiation damping of δ is taken into account!

These jumps + SR damping produce some equilibrium energy spread σ_δ: $\sigma_\delta = 0.66 \cdot 10^{-3}$ at E=80 GeV

The synchrotron motion and energy diffusion can be modeled without invoking of any information about the lattice of a ring! Essential input parameters are only: the equilibrium energy spread σ_δ, damping time τ_δ, synchrotron tune Q_s.

Parent resonances (due to vertical orbit distortions, mainly) are sitting on integers of the spin tune ν_0, which is defined as:

$$\nu_0 = \bar{\gamma} a = \bar{E}\text{(GeV)}/0.44064846.$$

Due to energy modulation by the synchrotron oscillations the higher order spin resonances are powered. They are spaced from the parent resonance $(\nu_0 = n)$ by the integer number of synchrotron tunes: $\nu_0 = n + m \cdot Q_s$

Their strength is proportional to $J_m(\xi)$ and raises promptly with the increase of ξ.

1. Equilibrium beam polarization degree simulation

The equilibrium polarization degree can be calculated as:

$$P = 92.6(\%)/(1 + \tau_{ST}/\tau_{dep})$$

where τ_{ST} is the Sokolov-Ternov polarization time, while τ_{dep} is the obtained by the spin tracking code depolarization time.

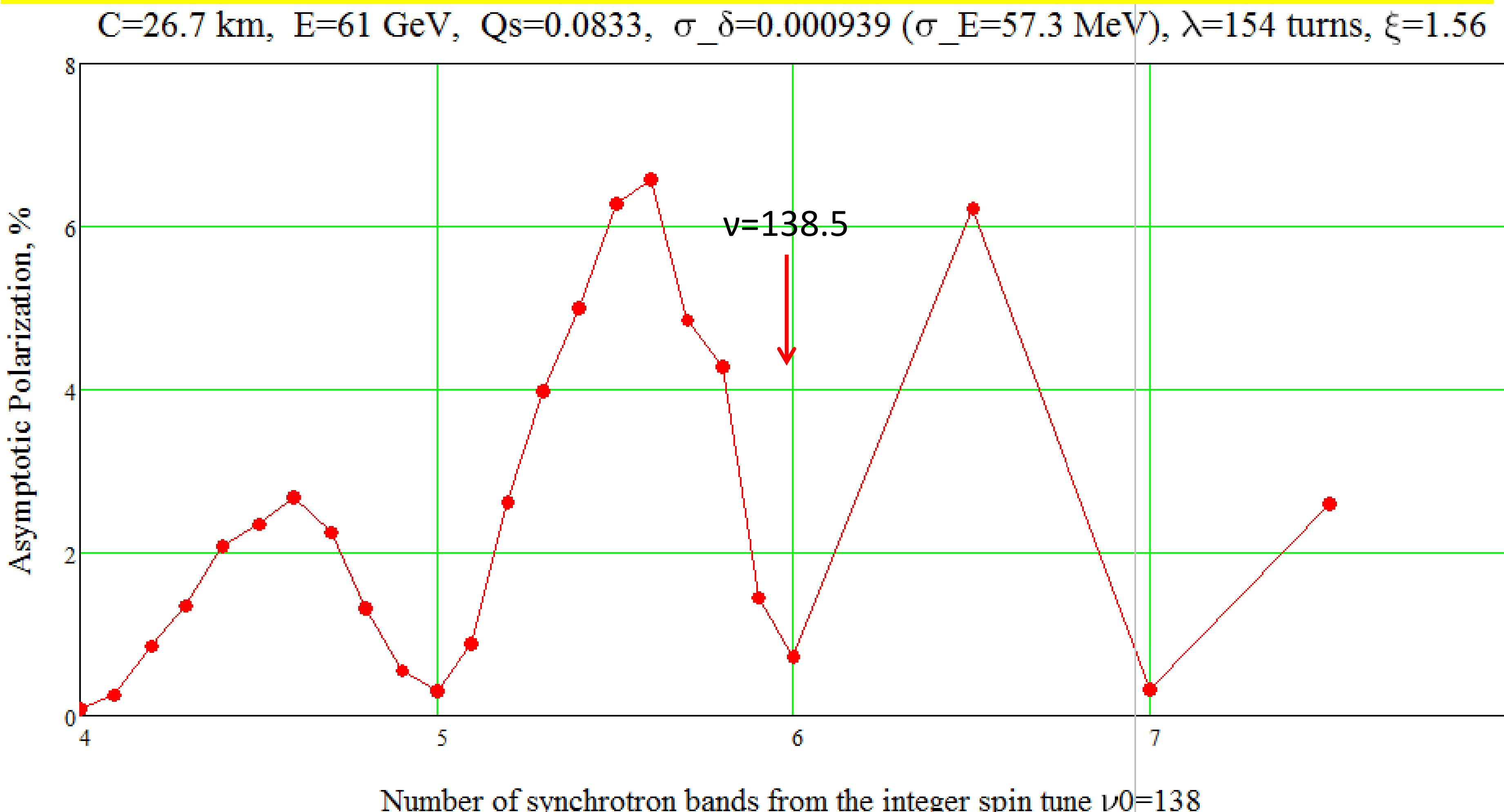
The harmonic spin matching, if applied as it was done at LEP and HERA, can minimize to some extent the strengths of few nearby resonances.

We rely on data from LEP at 61 GeV, where some polarization level, say about 6%, was observed (see R.Assmann et al. , "**Spin dynamics in LEP with 40–100 GeV beams**", AIP Conference Proceedings **570**, 169 (2001); doi: 10.1063/1.1384062).

This translates to estimation of some residual uncompensated spin perturbation: $w = 0.0015$, which we will use further as a reference.

Equilibrium polarization for LEP at 61 GeV, Qs=0.0833

The parent and the side band resonances are induced by the local spin rotation around the longitudinal axis by the angle $\varphi = w \cdot 2\pi$. Here $w = 0.0015$ was chosen to explain the polarization level observed at LEP experimentally. At such relatively high value of $Q_s = 0.0833$ dips at $m \cdot Q_s$ detunings from the parent resonance are quite pronounced.

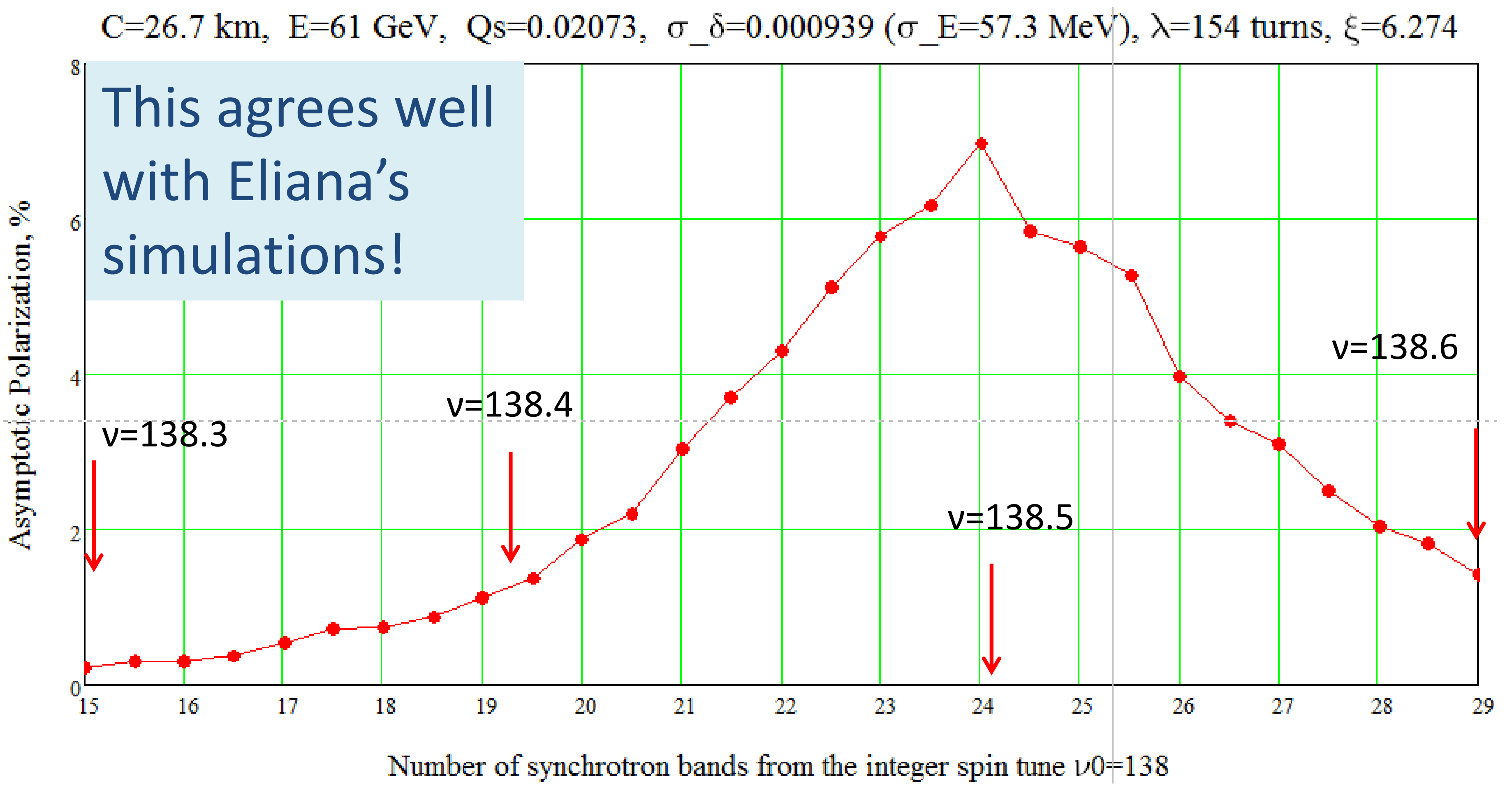


Equilibrium polarization for LEP at 61 GeV, Qs=0.02073

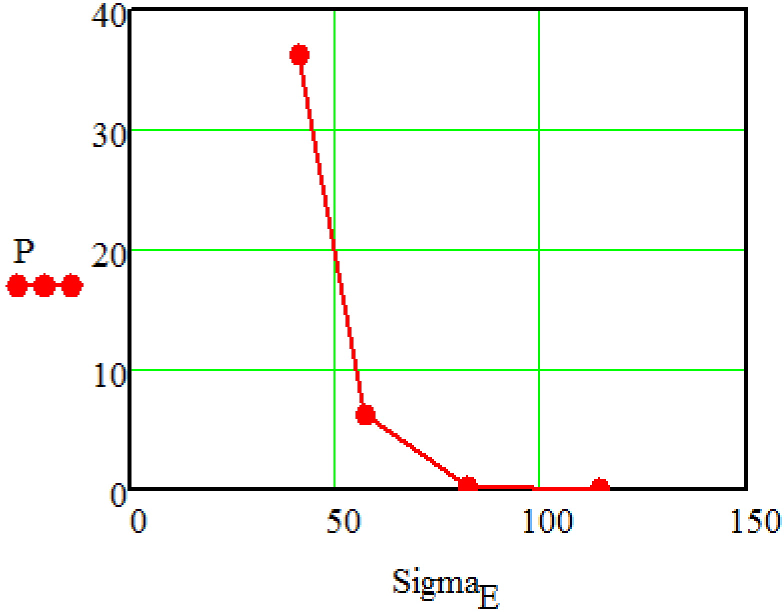
Here $w = 0.0015$, $Q_s = 0.02073$. Dips at integer detunings $m \cdot Q_s$ from the parent resonance $\nu = n$ disappear because of high m.

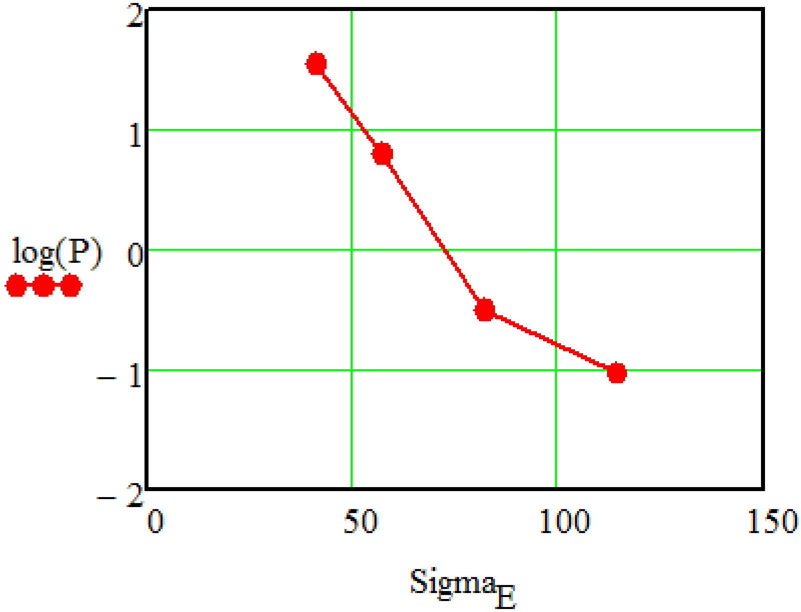
It is remarkable that polarization survives near half-integer spin tune values! Siberian Snake?

$J_m(\xi)$ is a rather small for m=20, $\xi = 6$: $J_{20}(6) = 10^{-9}$.



Polarization dependence on energy diffusion rate





Lessons from this study:

1) No strong influence of Qs on the attainable polarization level. Synchrotron modulation not too much important!
2) Only the value of beam energy spread is really important. Recommendation given from the LEP experience: $\sigma_E < 52\ MeV$ is confirmed by these simulations.

2. Resonant depolarization studies

RF flipper/depolarizer frequency: $\nu = f_{DP}/f_0$, with f_0 − revolution frequency

RF flipper/depolarizer strength – spin rotation around the longitudinal or transverse beam axis:

$$w = \begin{cases} B_{\parallel} l / 2\pi B\rho \\ \nu_0 \cdot B_{\perp} l / 2\pi B\rho \end{cases} \qquad (\nu_0 = \gamma a = 103.5 \text{ at } Z)$$

Frequency scanning rate: $\delta\nu = d\nu/dn.$ Here n – the number of turns

Typical values: $w = 3 \cdot 10^{-5} \div 5 \cdot 10^{-4}$
$\delta\nu = 1 \cdot 10^{-9} \div 1 \cdot 10^{-8}$

Froisart-Stora formula for reversing of polarization (dynamical depolarization!):

$$P(t \to \infty) = P(0) \cdot (2e^{-J} - 1) \qquad J = \pi^2 w^2 / \delta\nu$$

My simulations will show, that to depolarize a beam we shall adjust parameters to such values, that:

$$w^2/\delta\nu \cong 1 \qquad (\text{then } J \cong 10)$$

Scaling of resonant depolarization parameters

Assuming that we can narrow the energy search interval to $\pm 1\cdot 10^{-5}$, we may choose:

Reasonable spin tune interval to scan: $\Delta\nu_0 = \pm\, \nu_0 \cdot 10^{-5} = \pm 0.001$ (at Z and twice larger at W)

Frequency increment per turn: $\varepsilon' \equiv d\nu = 2\Delta\nu_0 \cdot / (f_0 \cdot \Delta t) = 0.002/3300\cdot 300 =$ **$2\cdot 10^{-9}$** ($6.7\cdot 10^{-9}$ Hz/s)

Now let evaluate the reasonable strength *w* of the depolarizer (tune provided by transverse RF-field). But first, let's define the parameter called as index of synchrotron modulation:

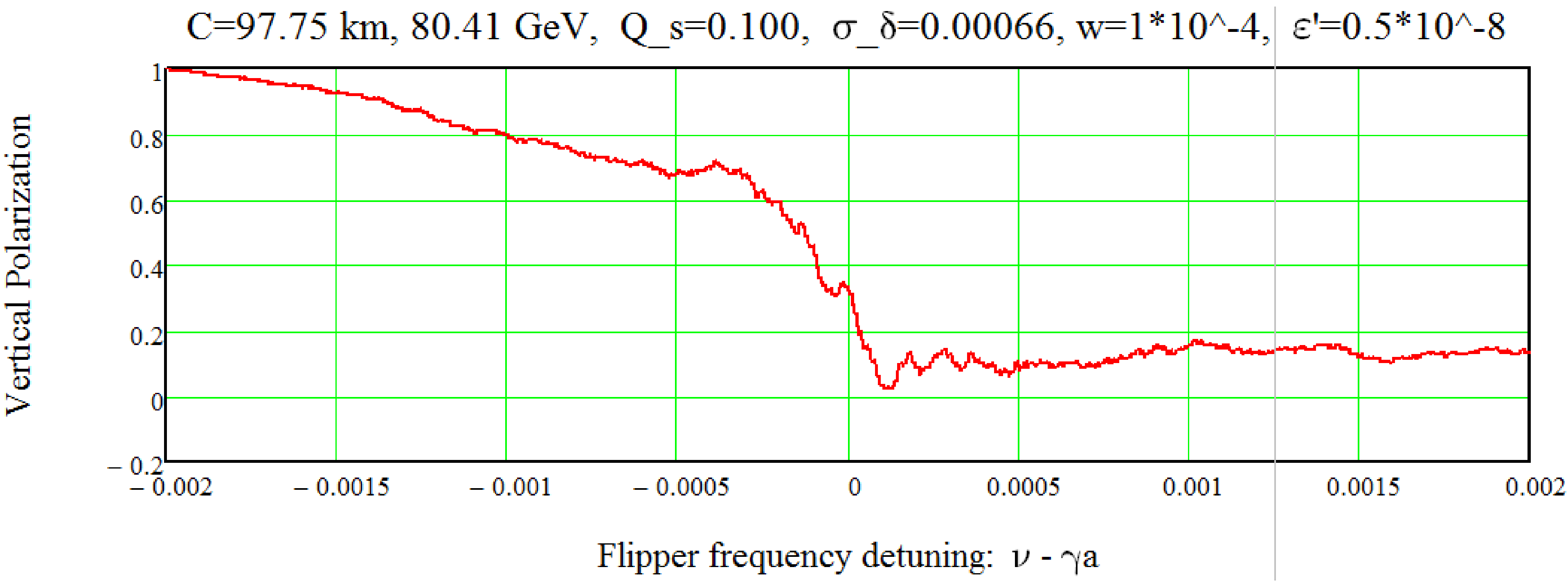
$$\xi = \nu_0 \sigma_\delta / Q_s \qquad \text{(With } \nu_0 = 182.5,\ \sigma_\delta = .00066,\ Q_s = 0.075 \ \rightarrow\ \xi = 1.6)$$

If this index is small $\xi < 1$, then minimal w is: $w^2/\delta\nu \cong 1 \quad \rightarrow \quad w = 4.5 \cdot 10^{-5}$

If this index is large, say $\xi = 1.6$, then: $(w \cdot J_0(\xi))^2/\delta\nu \cong 1 \quad \rightarrow \quad w =$ **$1.0 \cdot 10^{-4}$**

In fact, beam has a spread of amplitudes of synchrotron oscillations, therefore the depolarizer acts on different particles differently, according to spread of synchrotron modulation index. Still, fluctuations due to SR emission make random work and every particle is subjected to more or less equal depolarization effect. Here we shall remind that the width of the resonance zone will be crossed during many radiation damping times . At W τ_δ :=235 turns: $w/\delta\nu \cong 5 \cdot 10^4$ turns - this is about $200\ \tau_\delta$

FCC-ee at 80.41 GeV, Qs=0.100, $w=10^{-4}$, $d\nu=0.5\cdot10^{-8}$



$\nu_0 = 182.481$

$w^2/\varepsilon' = 2$

$(w \cdot J_0(\xi))^2/\varepsilon' = 0.9$

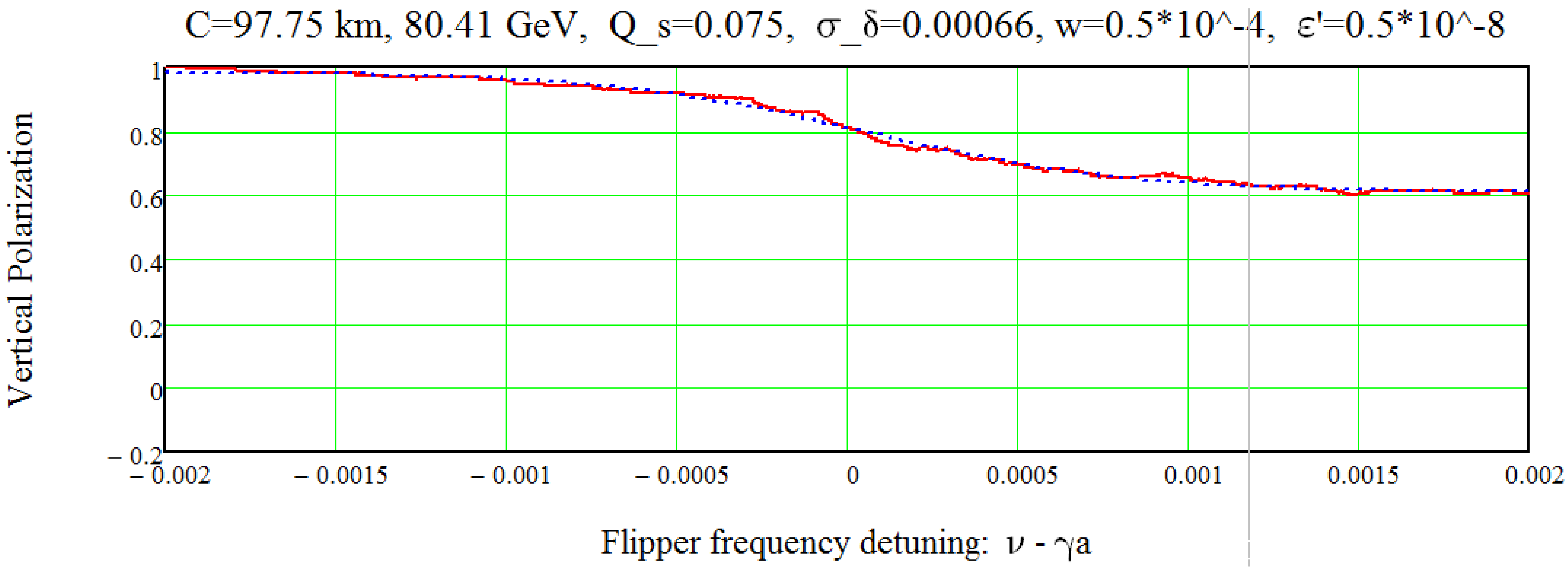
$\xi = \nu_0\sigma_\delta/Q_s = 0.87$

Scan time: T= 260.8 s

With such, relatively high value of the synchrotron tune, the localization of the resonance frequency is quite accurate.

Remind: the wanted accuracy is Δν=0.0001

FCC-ee at 80.41 GeV, Qs=0.075, w=.5·10^-4, dν=0.5·10^-8



$\nu_0 = 182.481$

$w^2/\varepsilon' = 0.5$

$(w \cdot J_0(\xi))^2/\varepsilon' = 0.1$

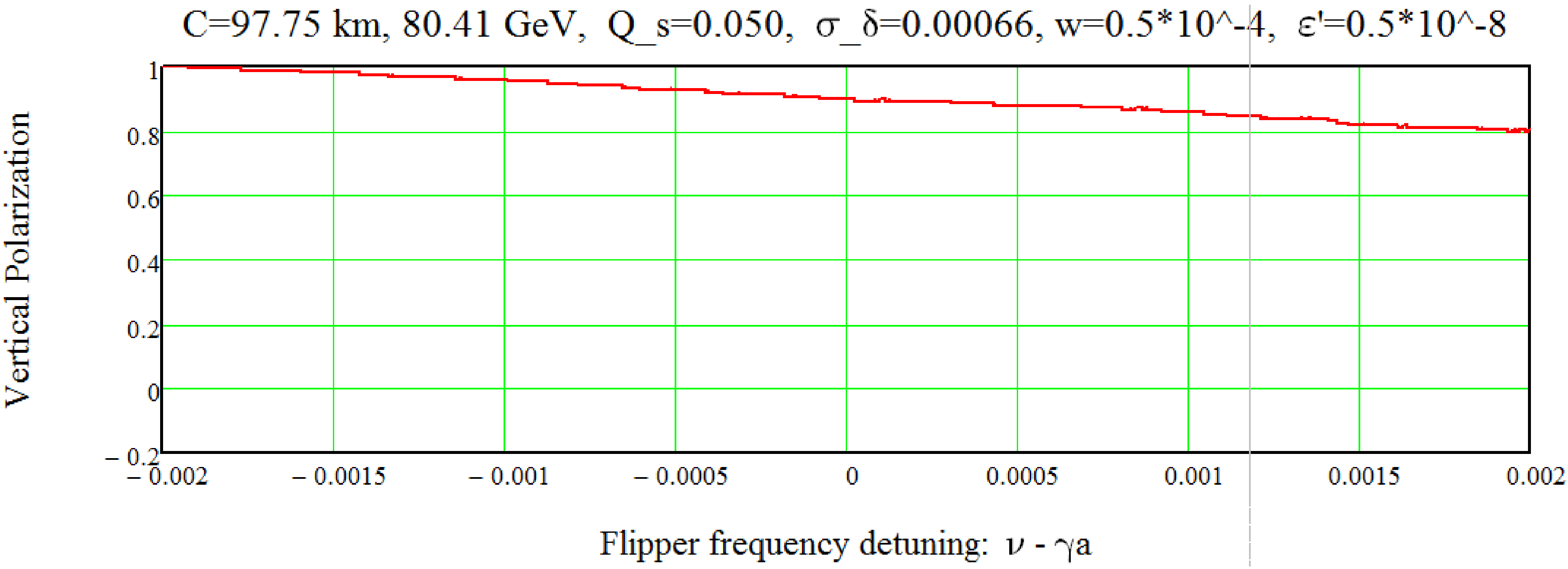
$\xi = \nu_0 \sigma_\delta / Q_s = 0.87$

Scan time: T= 260.8 s

With such, relatively low value of the depolarizer strength $w=0.5\cdot 10^{-4}$ and, subsequently, with low adiabaticity parameter $(w \cdot J_0(\xi))^2/\varepsilon' = 0.1$, a beam became only partially depolarized. A jump in polarization is about -37%.

Still, the applied fit by hyperbolic tangent (blue dots at the plot) shows small error Δν=0.00005 in determination of the crossing the resonance frequency point. Looks acceptable?

FCC-ee at 80.41 GeV, Qs=0.05, w=.5·10^{-4}, dν=0.5·10^{-8}



$\nu_0 = 182.481$

$w^2/\varepsilon' = 0.5$

$(w \cdot J_0(\xi))^2/\varepsilon' = 0!$

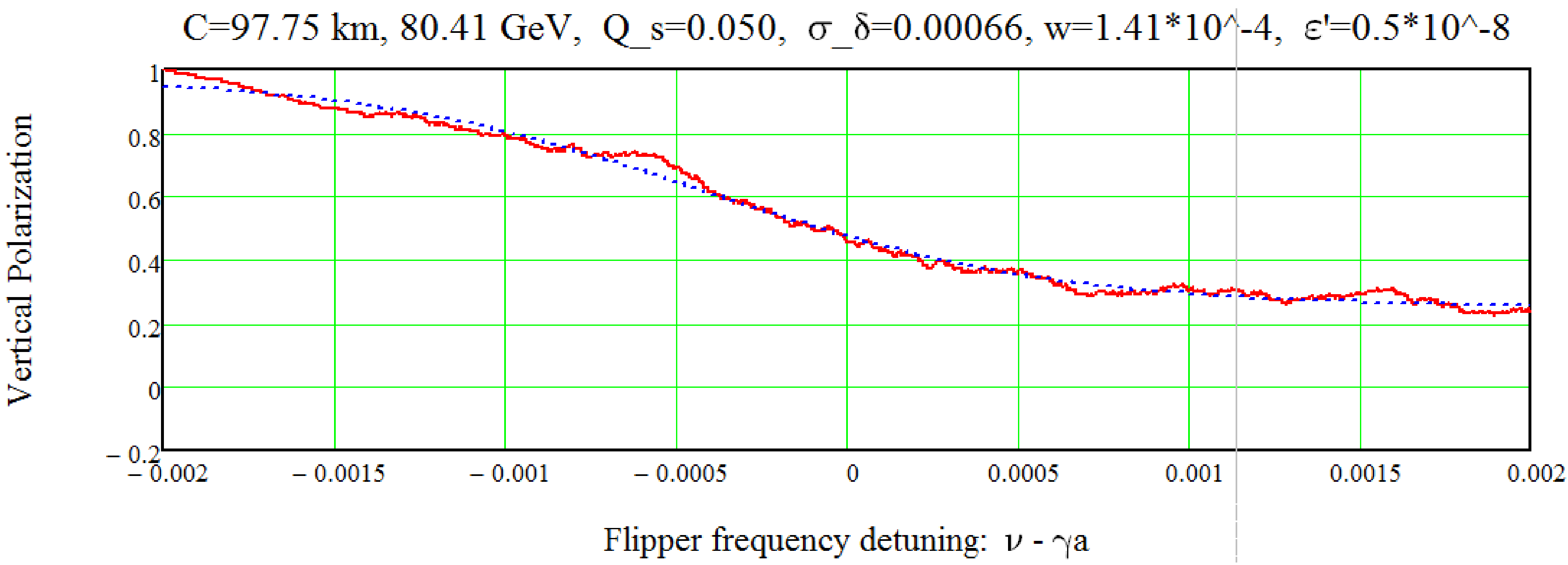
$\xi = \nu_0 \sigma_\delta / Q_s = 2.4$

Scan time: T= 260.8 s

With low values of the synchrotron tune Qs=0.05 and of the average value of Froissart – Stora parameter $(w \cdot J_0(\xi))^2/\varepsilon' = 0!$, depolarization process does not show any resonance!

This is due to high value of the average synchrotron modulation index: $\xi = \nu_0 \sigma_\delta / Q_s = 2.4$. Remind: $J_0(2.405)$=0.
Non-acceptable!

FCC-ee at 80.41 GeV, Qs=.05, w=$1.41\cdot10^{-4}$, dv=$0.5\cdot10^{-8}$



$\nu_0 = 182.481$

$w^2/\varepsilon' = 4$

$(w \cdot J_0(\xi))^2/\varepsilon' = 0!$

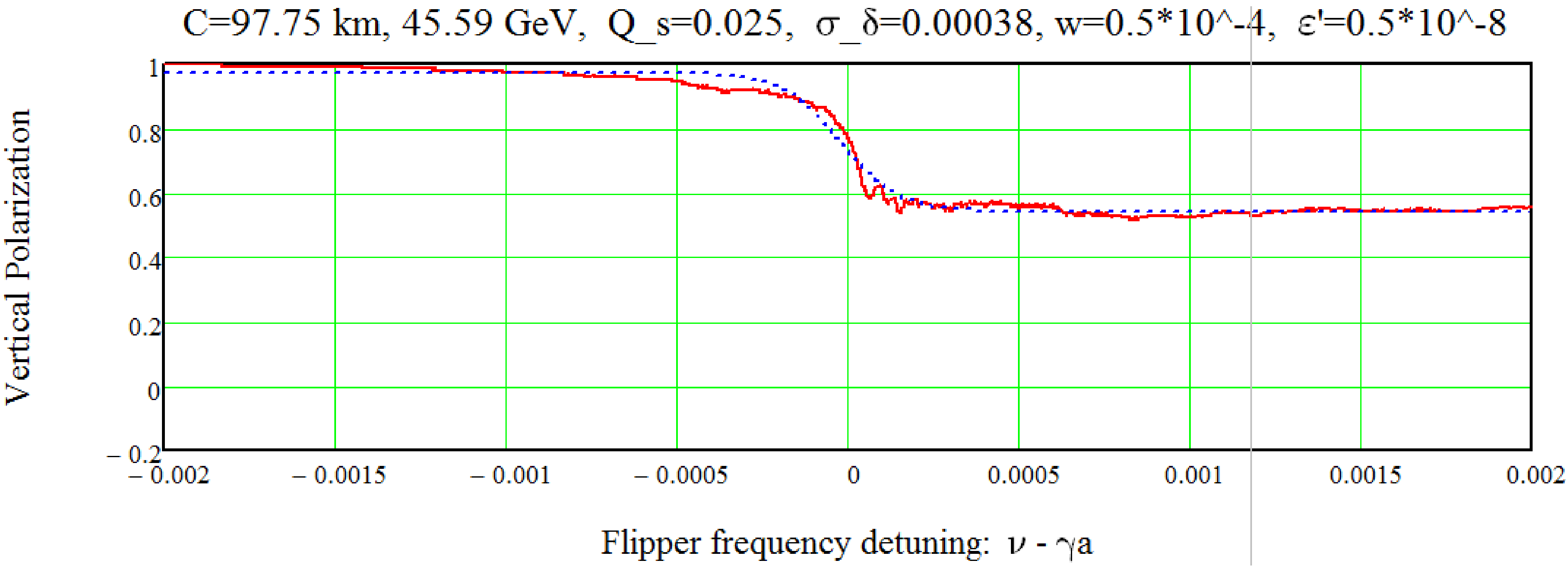
$\xi = \nu_0 \sigma_\delta / Q_s = 2.4$

Scan time: T= 260.8 s

Try to increase the depolarizer strength up to w=$1.41\cdot10^{-4}$. But not clear, trustable picture we see. Simple fit gives the resonance frequency with an error Δv= - 0.0004.

I think, the last two plots show that the synchrotron tune at W should be made much higher. Its minimal acceptable value is Qs=.075, or even higher!

FCC-ee at 45.6 GeV, Qs=.025, $w=0.5\cdot10^{-4}$, $d\nu=0.5\cdot10^{-8}$



$\nu_0 = 103.461$

$w^2/\varepsilon' = 0.5$

$(w \cdot J_0(\xi))^2/\varepsilon' = 0.115$

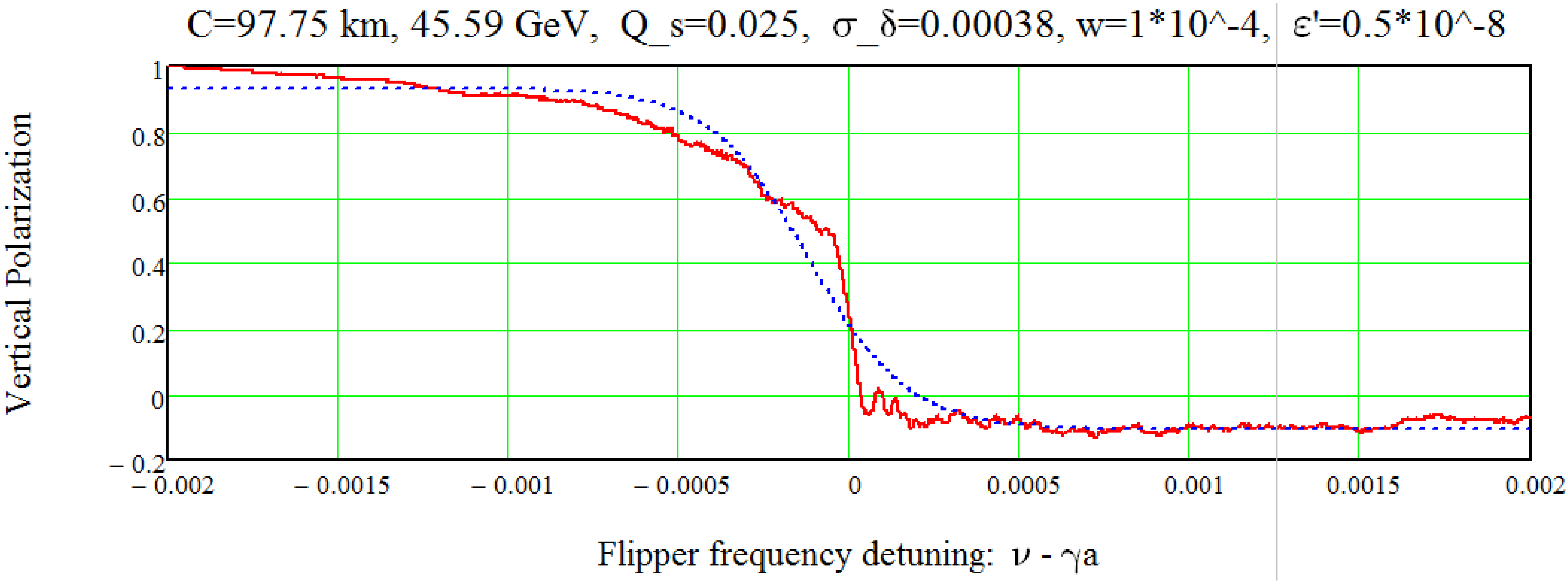
$\xi = \nu_0 \sigma_\delta / Q_s = 1.556$

Scan time: T= 260.8 s

With nominal Qs=.025 at Z. Due to high value of the synchrotron modulation index ξ=1.555 the effective value of Froissart-Stora parameter became too small $(w \cdot J_0(\xi))^2/\varepsilon' = 0.115$ and jump in depolarization level is only 40%.

My fit gives the resonance frequency with an error Δν= - 0.00002.

FCC-ee at 45.6 GeV, Qs=.025, w=1·10^{-4}, dv=0.5·10^{-8}



$\nu_0 = 103.461$

$w^2/\varepsilon' = 2$

$(w \cdot J_0(\xi))^2/\varepsilon' = 0.46$

$\xi = \nu_0 \sigma_\delta / Q_s = 1.556$

Scan time: T= 260.8 s

With nominal Qs=.025 at Z. And with strong depolarizer w=1·10^{-4}.

My simple fit gives the resonance frequency with an error Δv= - 0.00011. But, in fact, the transition zone here is very narrow and is centered to the right spin tune value very well.

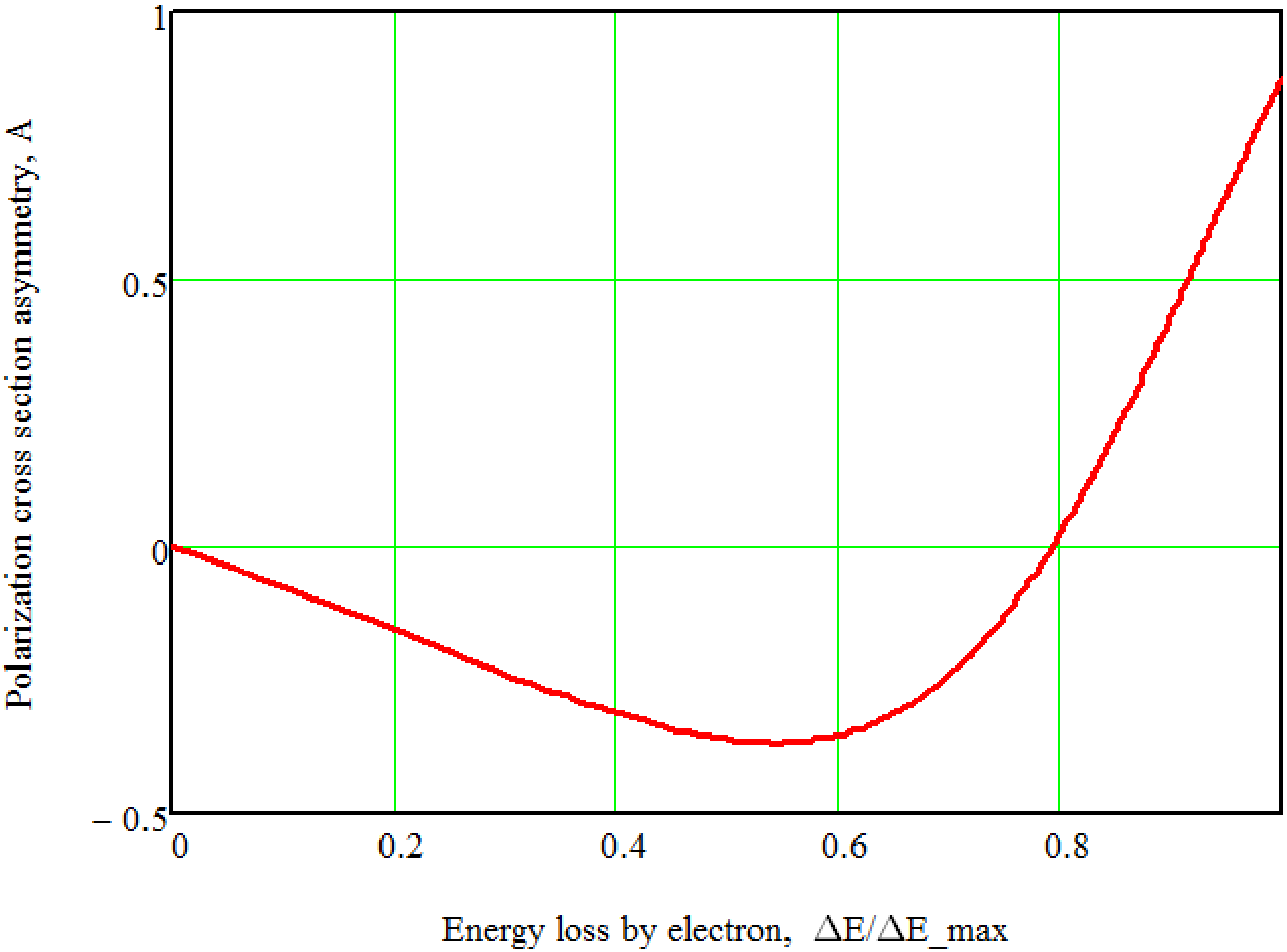
Conclusions on the resonant depolarization:

- At Z peak with the last set of beam and lattice parameters there is no obstacles to perform the Resonant Depolarization, even with such small synchrotron tune as Qs=.025.

- At W threshold there is a serious problem with the choice of too low Qs=.023 value. RD works, if Qs will be increased to 0.075, at least.

Longitudinal Compton Polarimeter

Compton cross section asymmetry for scattering of circularly polarized light on 80 GeV electron.



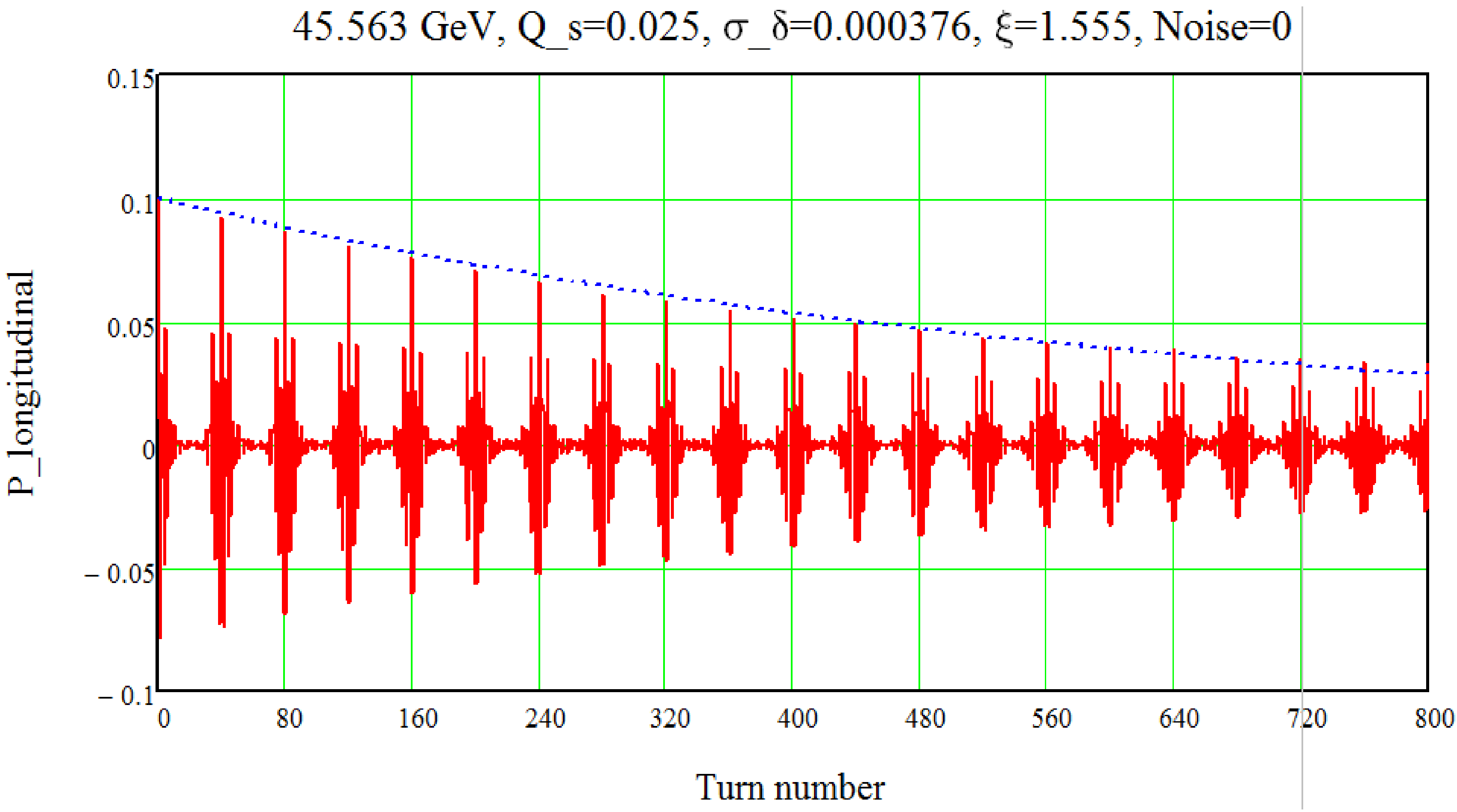
For polarization measurements is very beneficial to detect lost energy electrons instead of backscattered gammas!

We plan use the 2d-pixelized detector.

According to N. Muchnoi estimations of the counting rate, about 700 events /turn is expected with moderate laser power: 50 mJ/pulse, 3500 Hz repetition frequency, 10^{10} electrons/bunch. This translates to 12% of statistical noise for polarization.

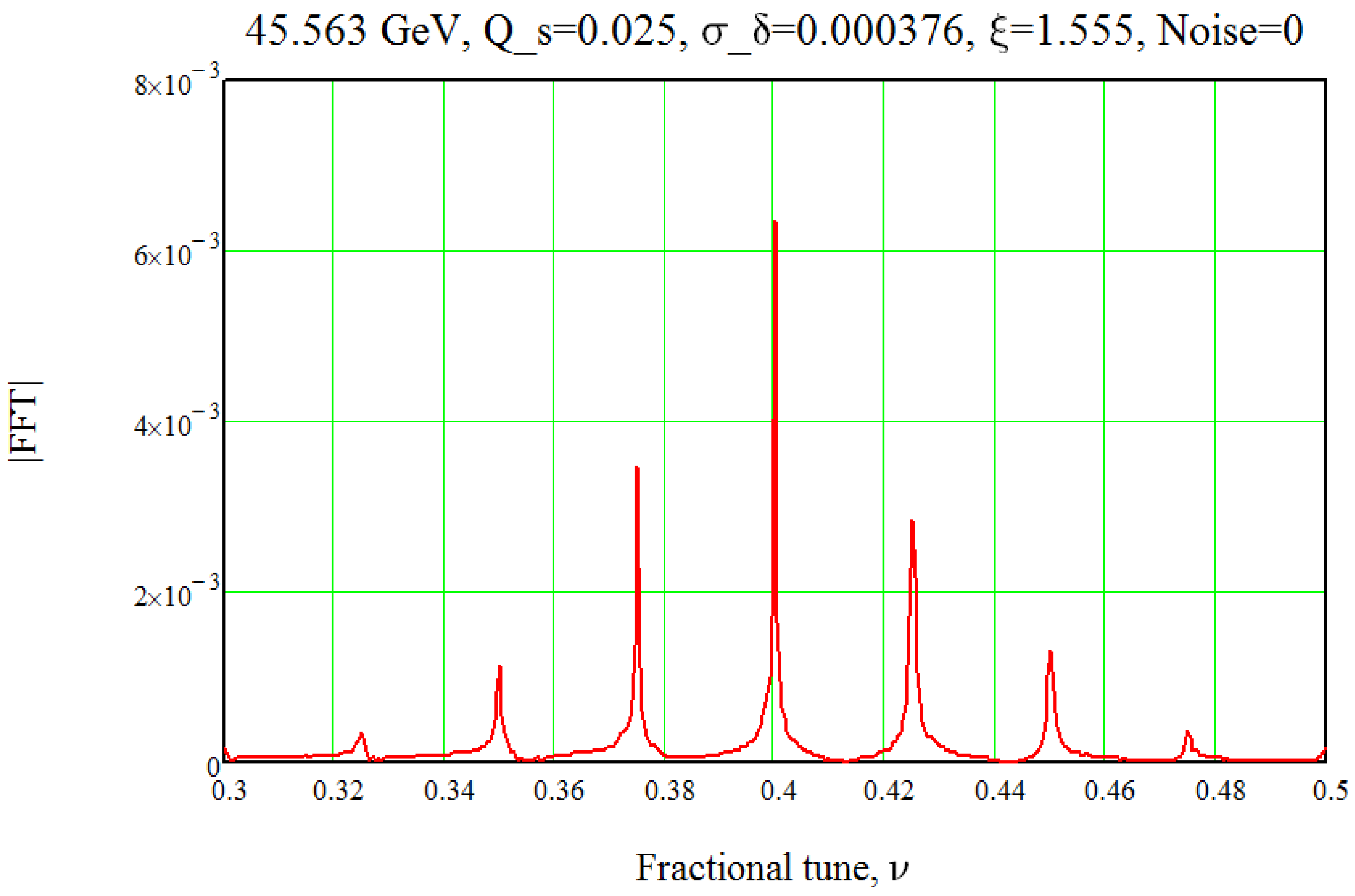
3. Precession approach. Example with 45 GeV spin ensemble.

Turn by turn plot for the longitudinal polarization component: beam energy E=45.563 GeV. One can see polarization echoes at integer numbers of the synchrotron periods – each 40-th turn. The dotted line is the exponential fit with τ=640 turns, which describes the long term decoherence. Initial polarization level (in the horizontal plane) is P=0.1.



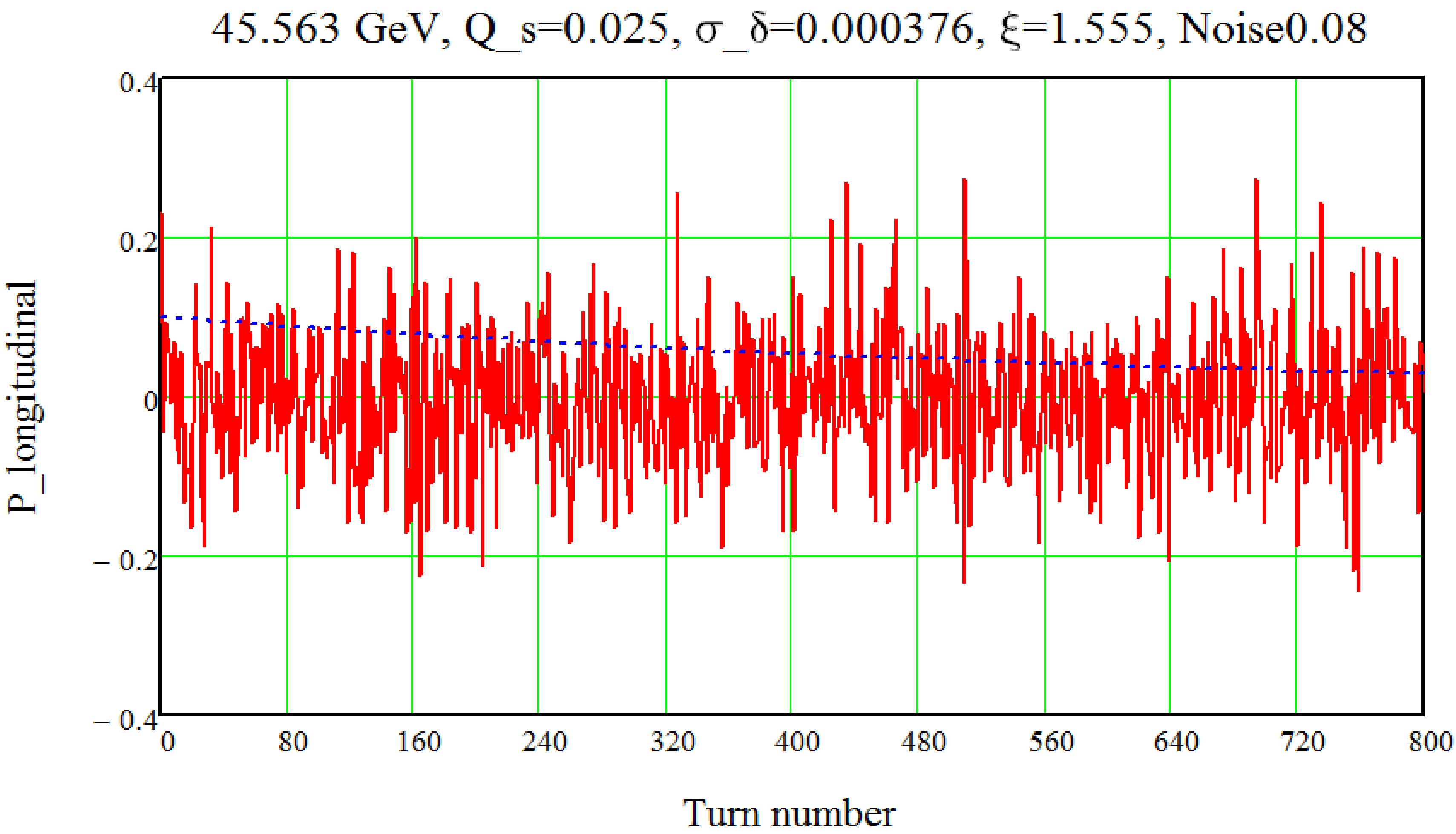
FFT of 45 GeV beam free precession

Fast Fourier Transform (FFT) for beam energy E=45 GeV, Q_s=0.025, N=2048 turns, Np=4000 particles, as it will be recorded by the ideal longitudinal polarimeter (means - no statistical noise in measuring of the polarization level).



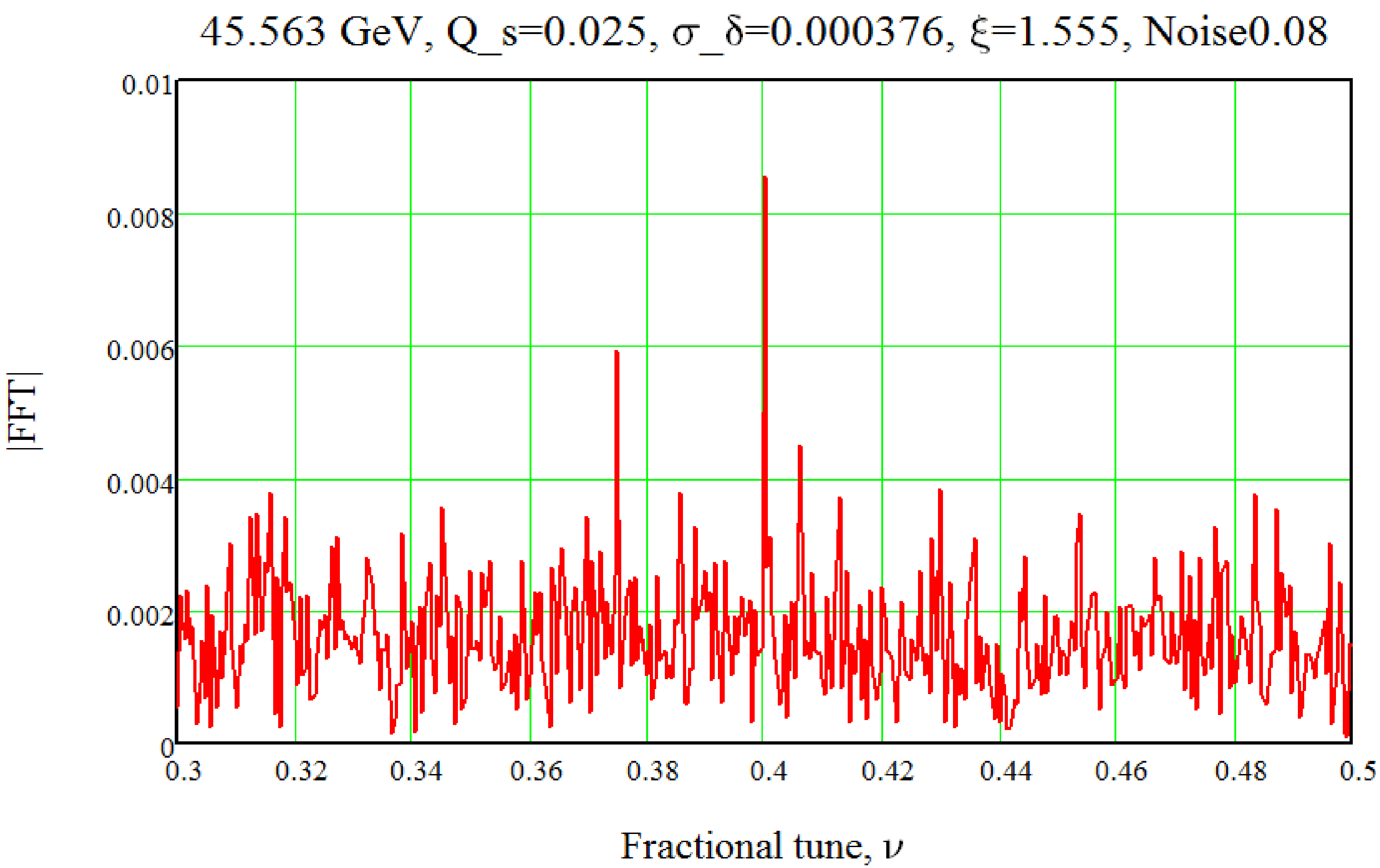
Precession signal with the statistical noise added

Turn by turn plot of the longitudinal polarization component for a beam energy E=45 GeV with polarimeter statistical noise σ_{noise}=0.08 added to a signal.



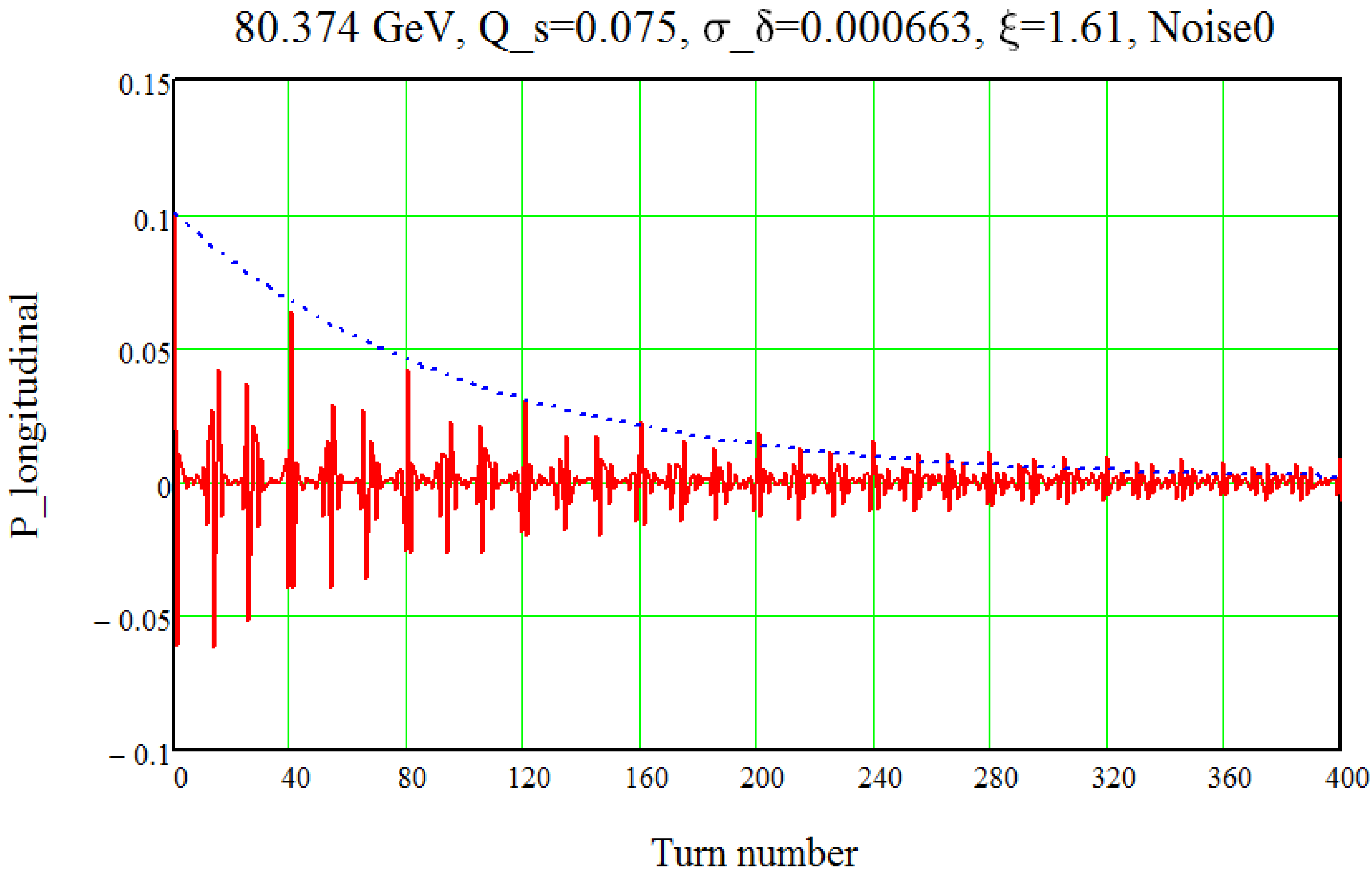
Spectrum of 45 GeV signal with a noise

Fast Fourier Transform for a beam energy E=45.563 GeV, Q_s=0.025, N=2048 turns, Np=4000 particles. A polarimeter statistical noise σ_{noise}=0.08 is added to a signal. Still the wanted signal peak ν=0.400 is seen here almost at a right position.



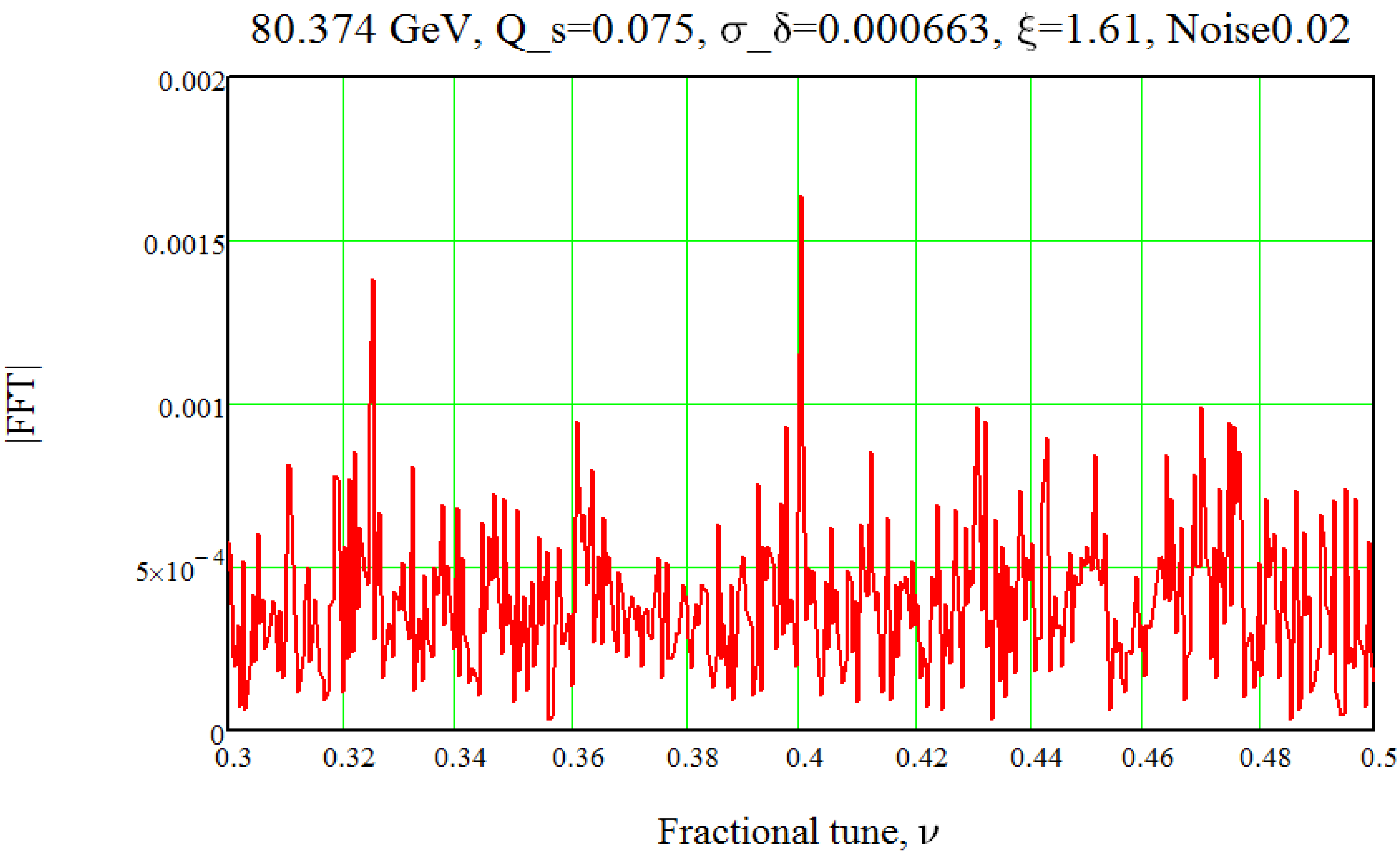
Free precession signal of 80 GeV beam

Spin precession echoes for the case E=80 GeV, Q_s=0.075 and σ_δ=0.000663. No any statistical noise is added here! Free precession starts from a level P=0.1. The long decoherence time is equal to τ=100 turns, only.



Spectrum of 80 GeV beam with a noise

Fast Fourier Transform for a beam energy E=80.374 GeV, Q_s=0.075, N=2048 turns, Np=4000 particles, σ_{noise}=0.02. The precession peak is located at ν=0.4. A synchrotron side band at ν=0.325 is clearly visible, but not so at ν=0.475.



Summary on free precession approach:

Beam energy, E (GeV)	Spin tune, ν_0	Relative energy spread, σ_δ	Synchro-tron tune, Q_s	Modulation index $\xi = \nu_0 \sigma_\delta / Q_s$	Spin De-coherence time, τ (turns)	Statistical noise limit, σ_{noise}
45.5	103.4	0.000376	0.025	1.555	640	0.08
45.5	103.4	0.000376	0.050	0.777	2560	0.15
45.5	103.4	0.000376	0.075	0.518	5760	0.50
80.4	182.4	0.000663	0.050	2.419	40	0.01
80.4	182.4	0.000663	0.075	1.613	100	0.02
80.4	182.4	0.000663	0.100	1.210	145	0.05

To be able to measure the spin free precession frequency using the longitudinal Compton backscattering polarimeter the last should provide at 80 GeV very good sensitivity to single turn polarization level: better than 1-2 %. Qs should be as large as 0.075.

Thank you for your attention!