Ideas for longitudinal polarization at the Z/W/H/top factory

I.Koop
Budker Institute of Nuclear Physics,
Novosibirsk State University,
Novosibirsk State Technical University,
630090, Novosibirsk, Russia

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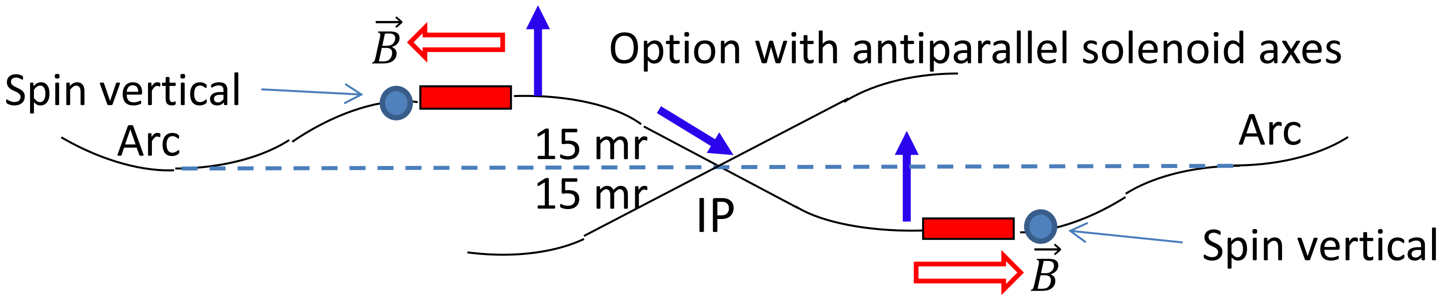
Outline

- Longitudinal polarization scheme with restoration of vertical spin direction in arcs
- Spin transparent solenoid type spin rotators
- Adiabatic acceleration of polarized beams in a booster synchrotron
- Depolarization rates estimations
- Conclusion

Optimal option for longitudinal polarization at Z



- Antisymmetric chicane plus two 90^0 solenoid type spin rotators. Opposite polarities of left-right from IP magnetic fields cancel spin direction chromaticity outside of the insertion. Spin tune unchanged!

Spin rotation ϕ by the half-chicane (angle α):

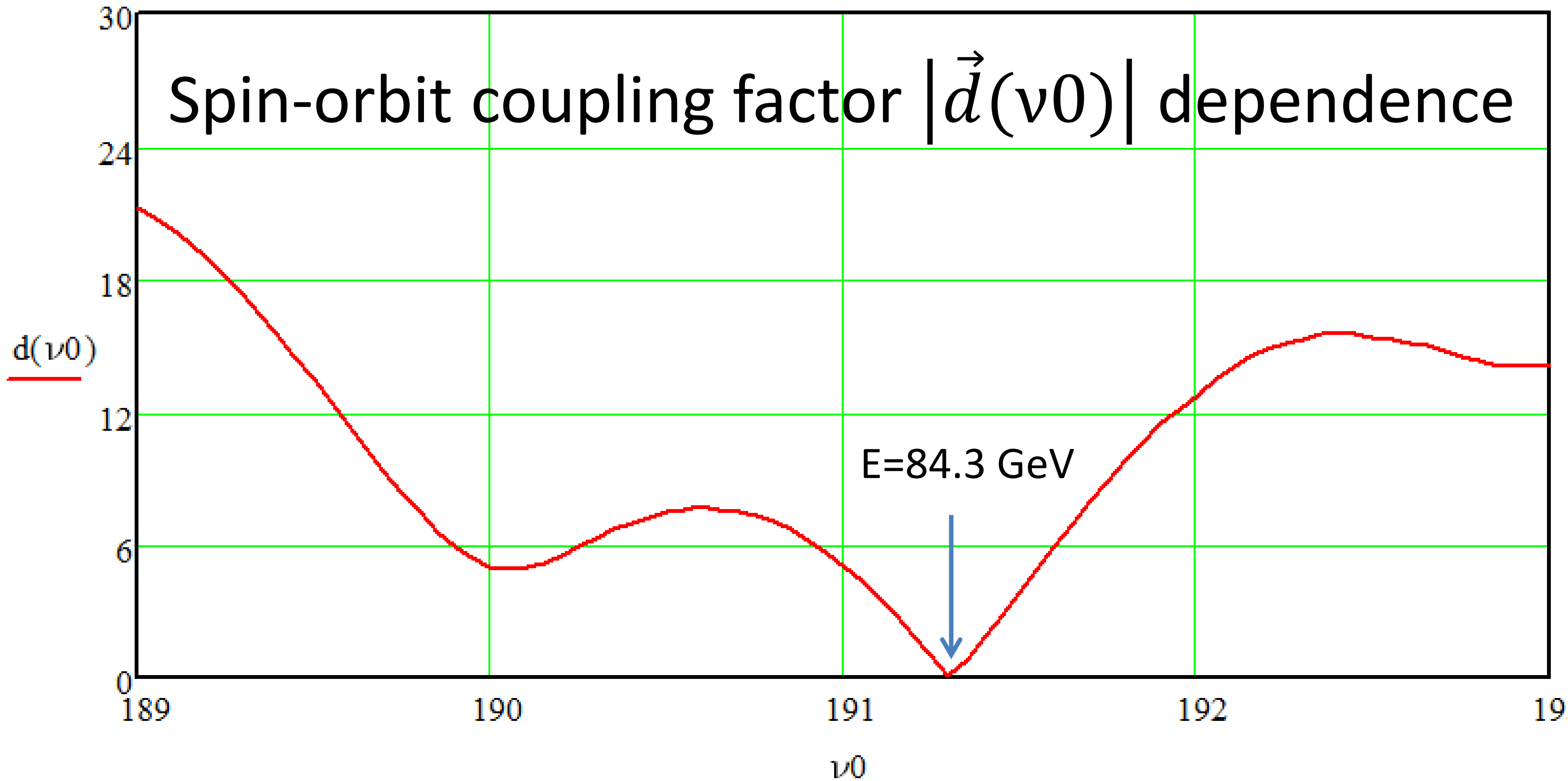
$$\phi = \frac{\pi}{2} \quad \rightarrow \quad \alpha = \frac{\phi}{\nu_0} = 15\ \mathrm{mr}\ (\mathrm{at}\ Z\ \nu_0 = 103.5)$$

Tolerance: $\Delta\alpha = \pm 5$ mr

In this option only the chicane magnets contribute to the radiative depolarization, therefore the spin depolarization time at Z exceeds 24 hours! But beamstrahlung will decrease it, say to 1-2 hours. Still OK!

Alternative option: rotators with not parallel axes

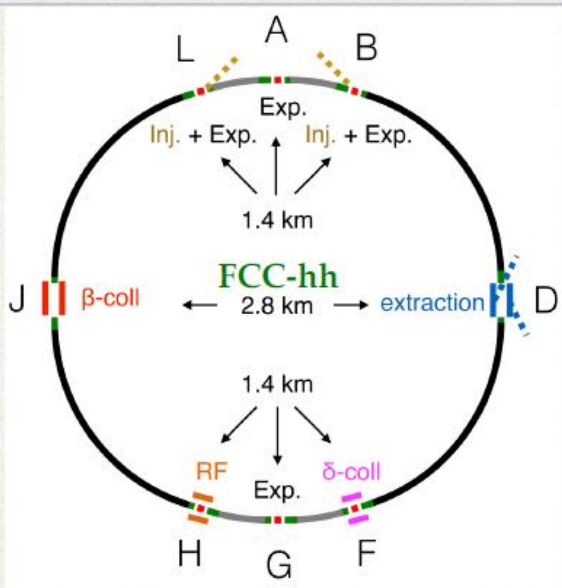
A ring with two insertions, each made of two $\pi/2$ spin rotators, separated by an arc $\phi = \pi/\nu 0$. Let be $|\vec{d}|$=0 at $\nu 0$=191.3. Then expect much stronger depolarization at nearby energy points, where d>>1.

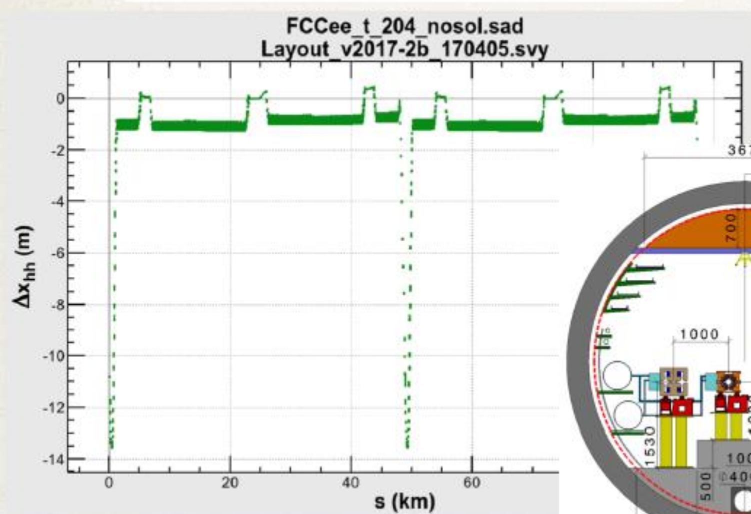


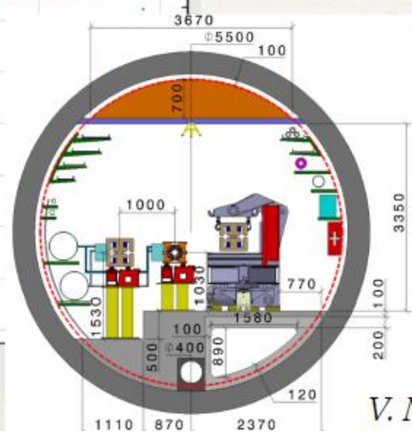
This option looks unacceptable for W. For Z can be considered, because of lower $\nu 0$.

FCC-ee layout

Layout of FCC-ee







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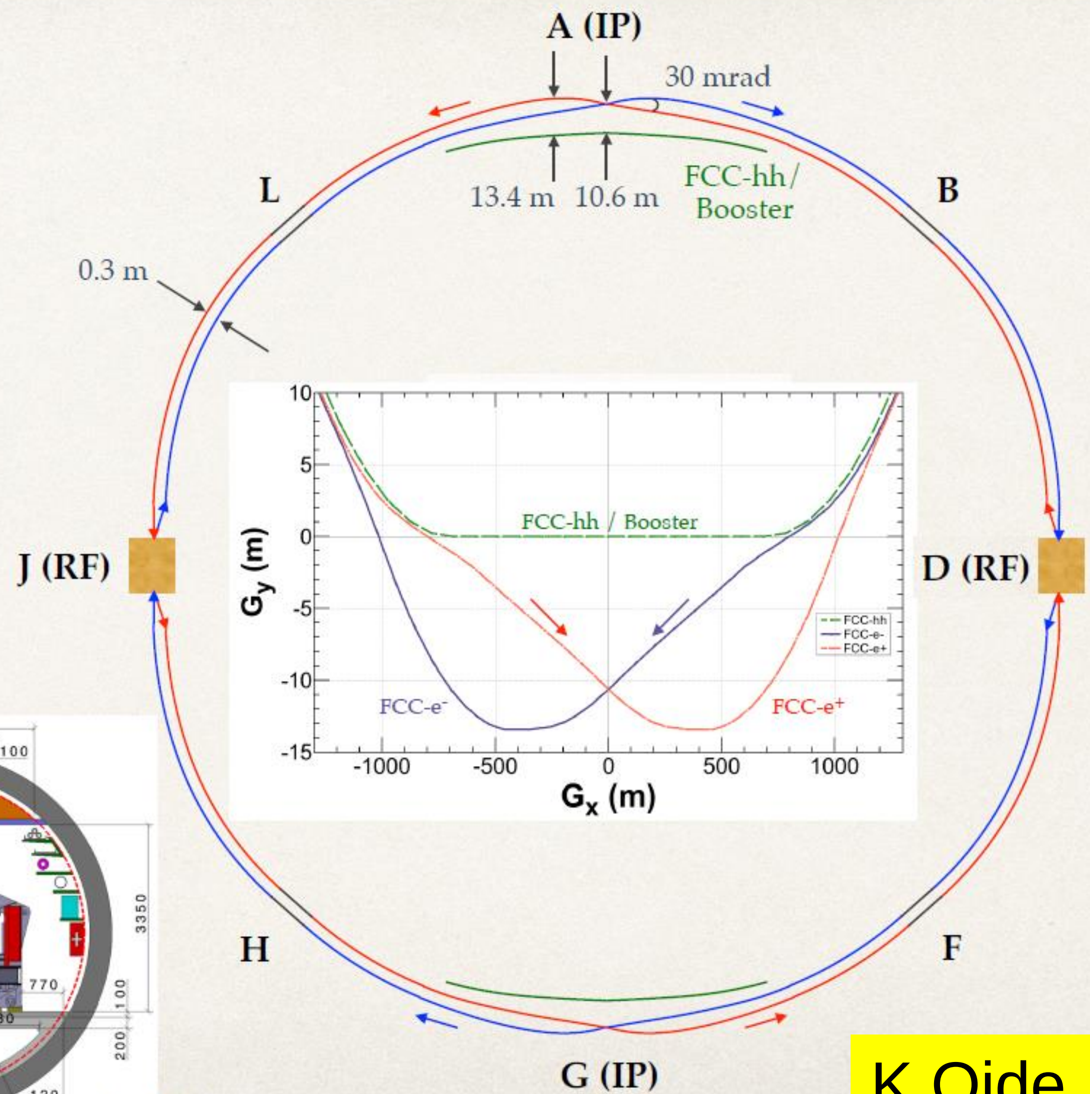

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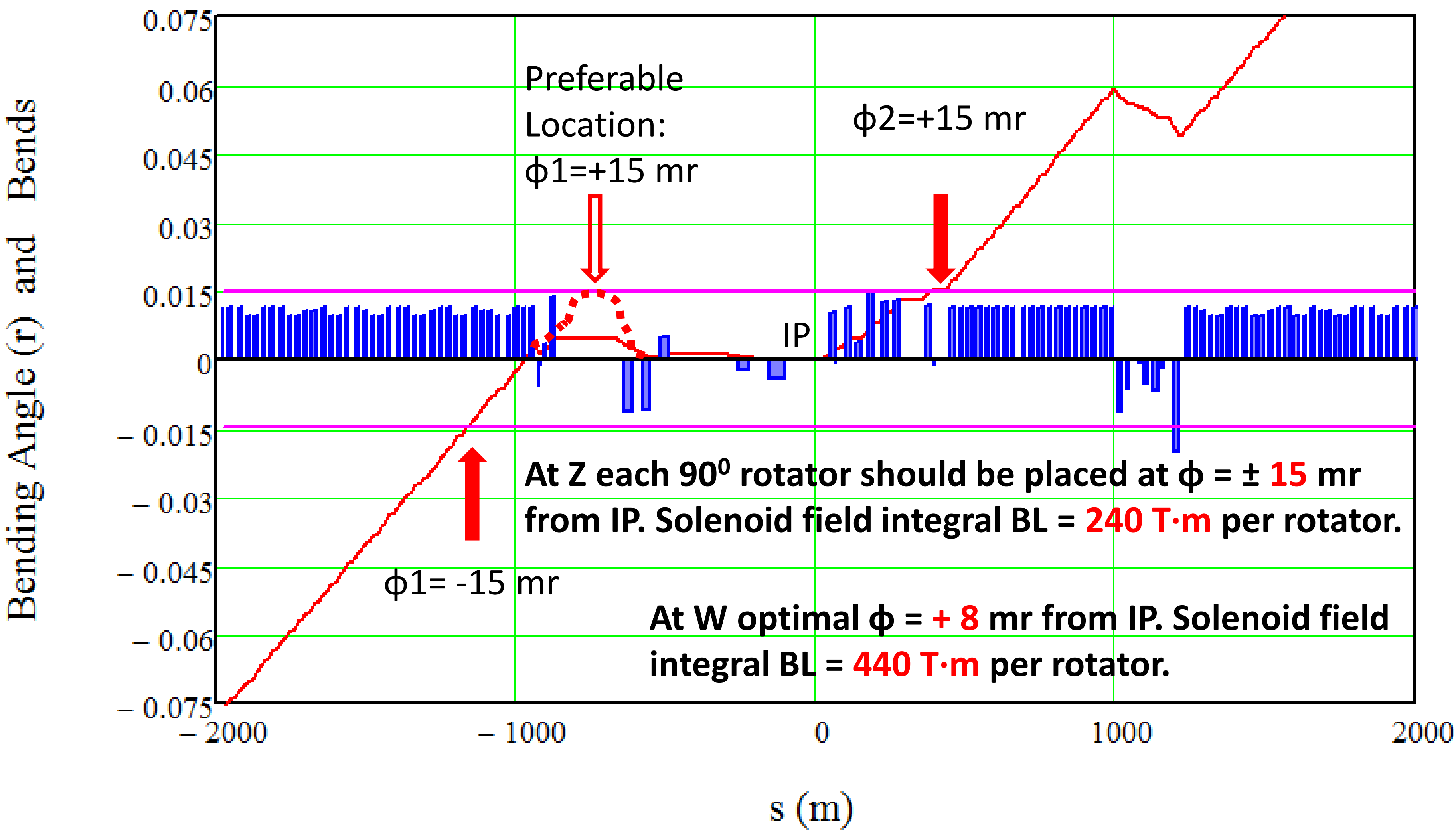
Possible locations of Spin Rotators at FCC-ee



Lattice shall be modified to provide long drift for the left Spin Rotator at ϕ1 = +15 mr from IP.
Version with ϕ1= -15 mr for the left rotator is not as good as option with ϕ1= ϕ2= +15 mr.

Spin transparent rotator for the solenoid partial Snake

For decoupling should be $T_x = -T_y$

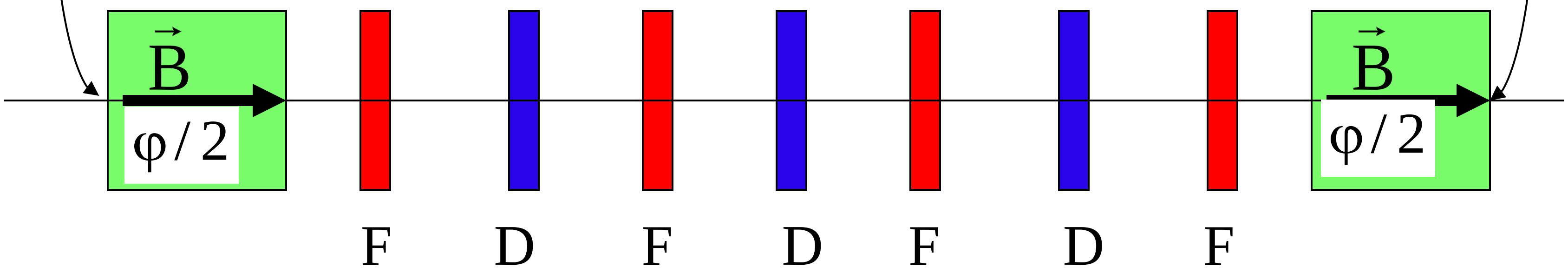
Litvinenko, Zholentz, 1980

$$T_x = \begin{pmatrix} -\cos\varphi & -2r\sin\varphi \\ (2r)^{-1}\sin\varphi & -\cos\varphi \end{pmatrix}$$

for the spin transparency!

(Koop et al., SPIN2006)

$r = pc/eB$



Two solenoids, each L=24 m, B=5 T, provide spin rotation by $\varphi = 90^0$ at E=45.6 GeV. Extension to E=82 GeV with B=9 T looks feasible.

All quads don't need to be skewed! Spin transparency require:

Full Snake: $\cos\varphi = -1, \quad \sin\varphi = 0$; 90^0 - spin rotator: $\cos\varphi = 0, \quad \sin\varphi = 1$

Polarized beams in a booster synchrotron

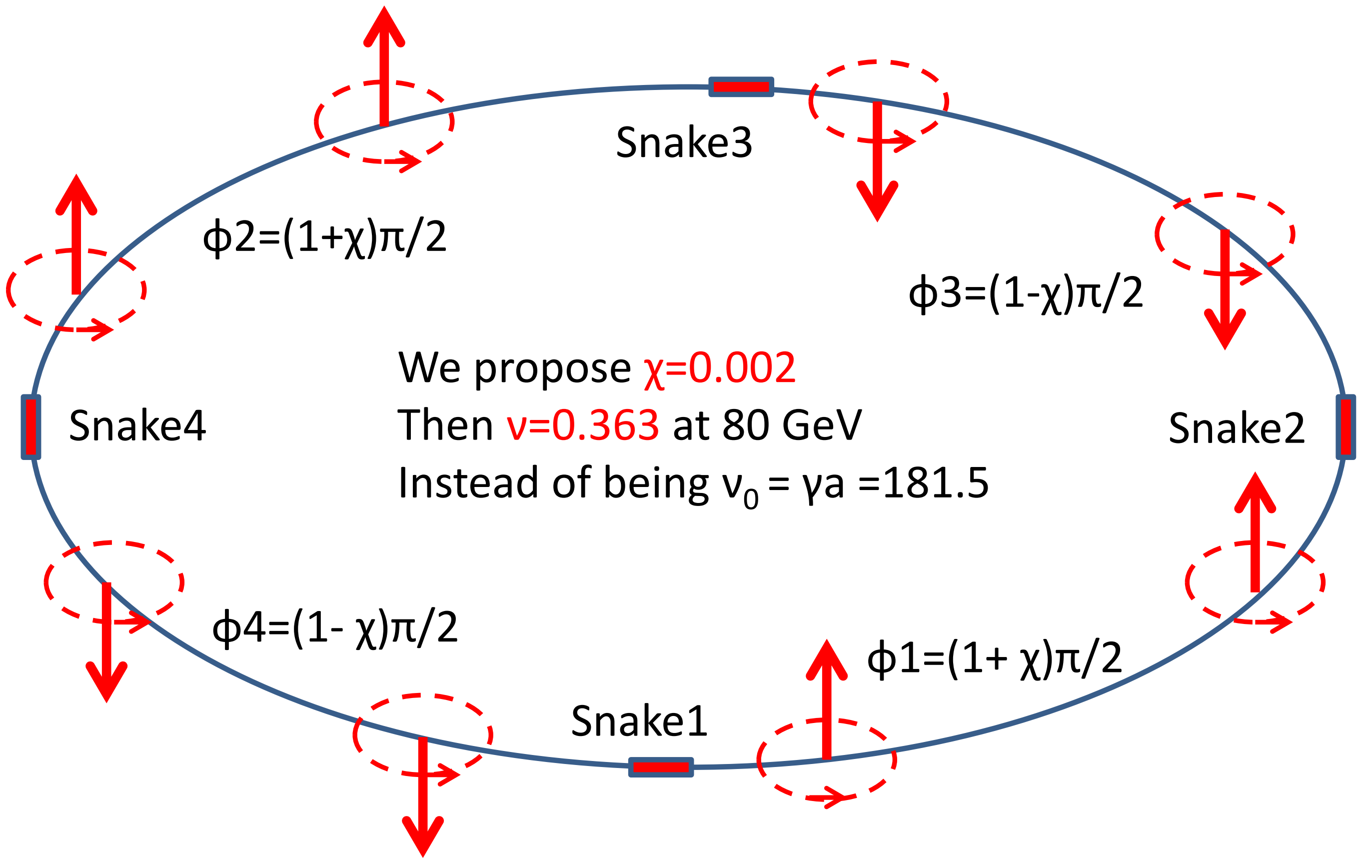
Three options will be presented in next slides:

1. Scheme with even number of Snakes – good but technically difficult for realization (strong ramping solenoids are needed).

2. Fast energy ramping without any Snake – needs faster energy ramping than it is supposed.

3. Adiabatic crossing of integer resonances by use of Partial Snake with static solenoids – most promising solution!

Opion 1: Four Snakes and arcs in between

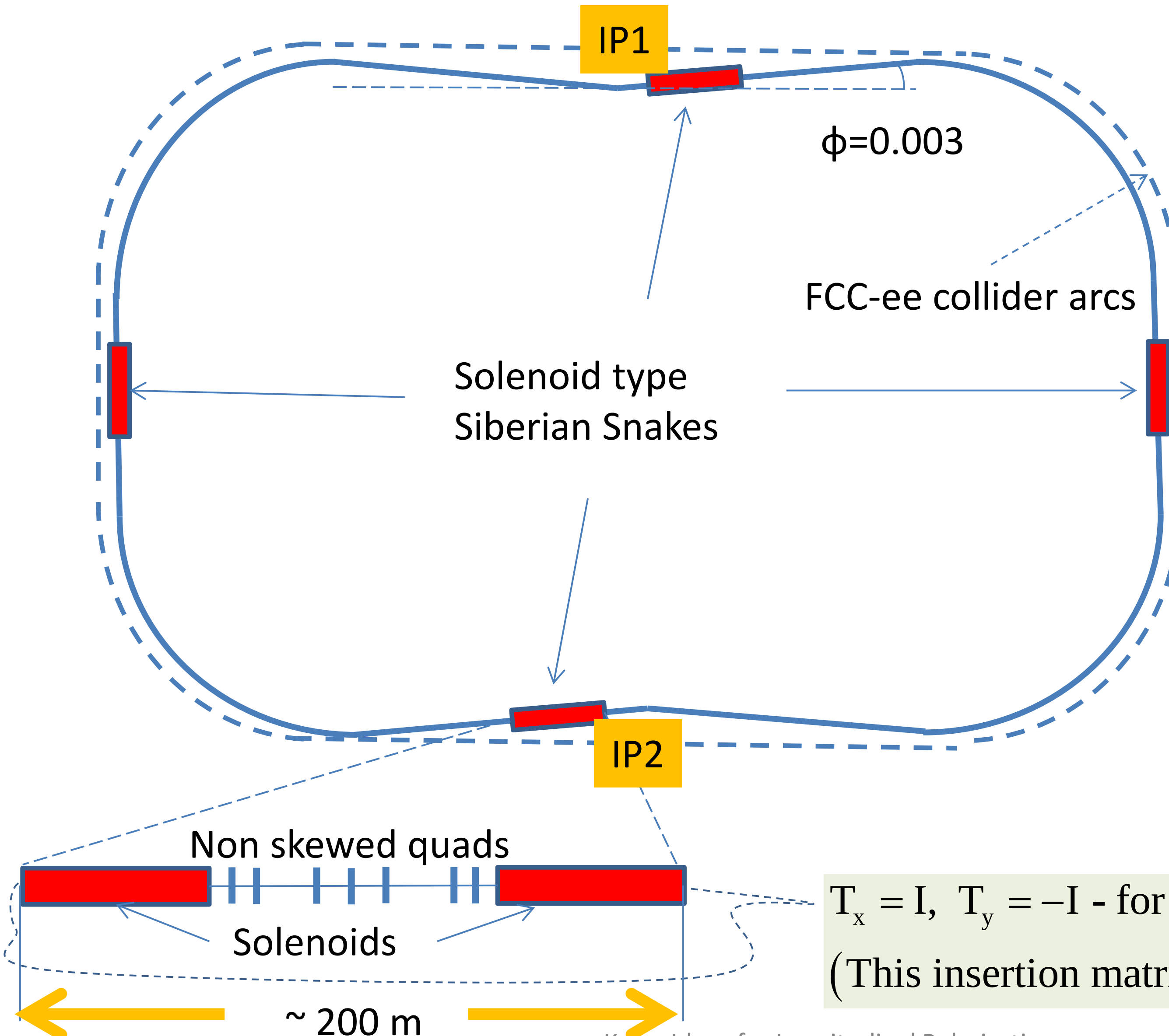


In 70-th such approach was considered by A.Kondratenko, for FCC discussed by S.R. Mane In arXiv:1406.0561v1 physics.acc-ph 3 Jun 2014.

The equilibrium spin is altering , be directed upright or down in arcs. Four Siberian Snakes rotate spin by 180^0 around the longitudinal axis.

The spin precession frequency will be zero in case of equally spaced snakes.
To avoid zero spin tune a small asymmetry of successive arcs has to be foreseen: $\phi=(1 \pm \chi)\pi/2$.
Now spin tune $\nu= \chi \cdot \nu_0$ became reduced to $\nu=0.363$, if $\chi=0.002$, $\nu_0 =181.5$. Here $\nu_0=\gamma a$ – unperturbed spin tune, where a=0.001159652187 is anomalous magnetic moment.

How the arcs asymmetry can be made



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:

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

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

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

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 $\left\langle \vec{d}^2 \right\rangle = 4000 \quad \rightarrow \quad \tau_d \approx 18\ \mathrm{s}$

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

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=2500

Statistically indepent N kicks will produce the total spin rotation:

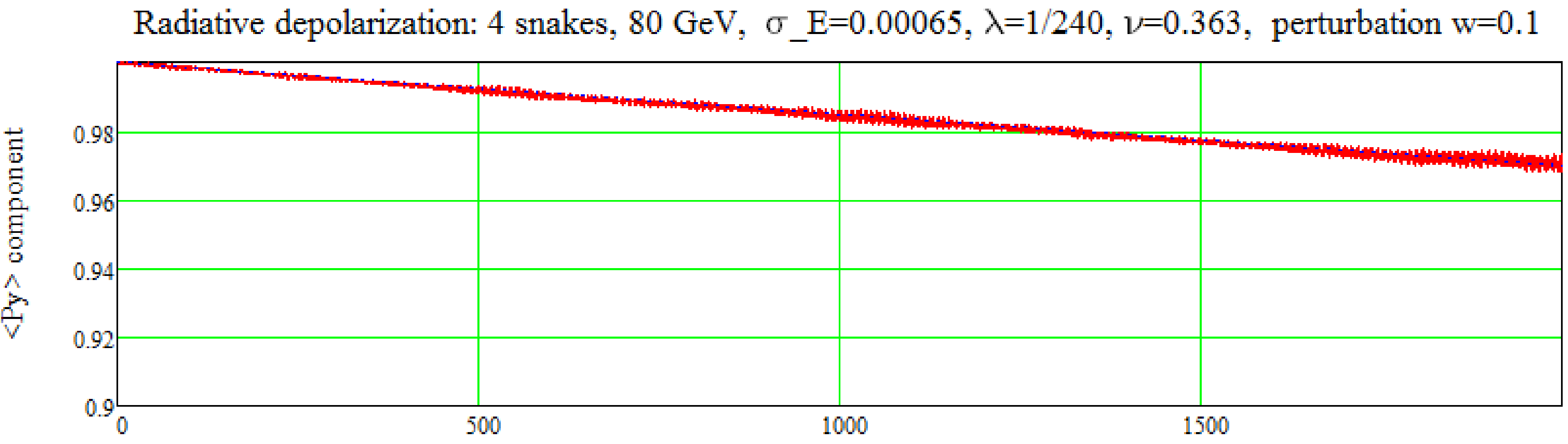
$\varphi_\Sigma = \nu_0 \cdot \Delta y_1^{'} \cdot \sqrt{N}$ Now we want: $\varphi_\Sigma \le w \cdot 2\pi,$

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

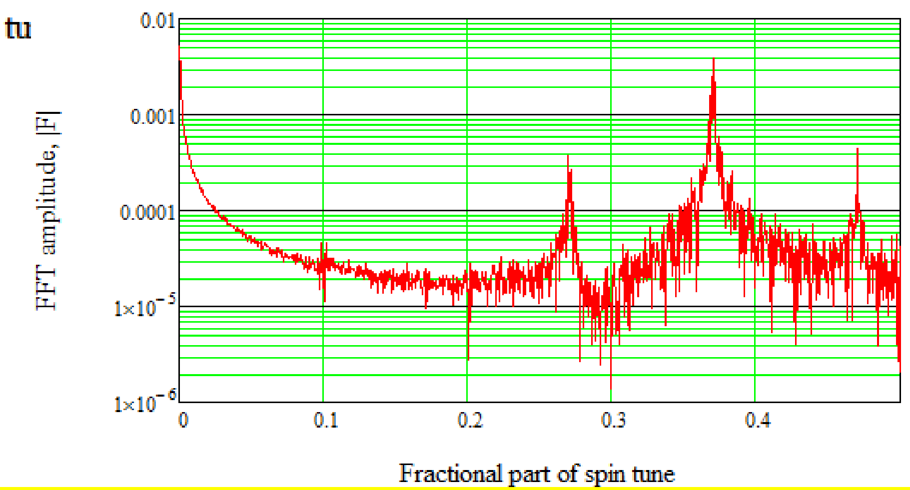
Spin tracking of the depolarization process



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.

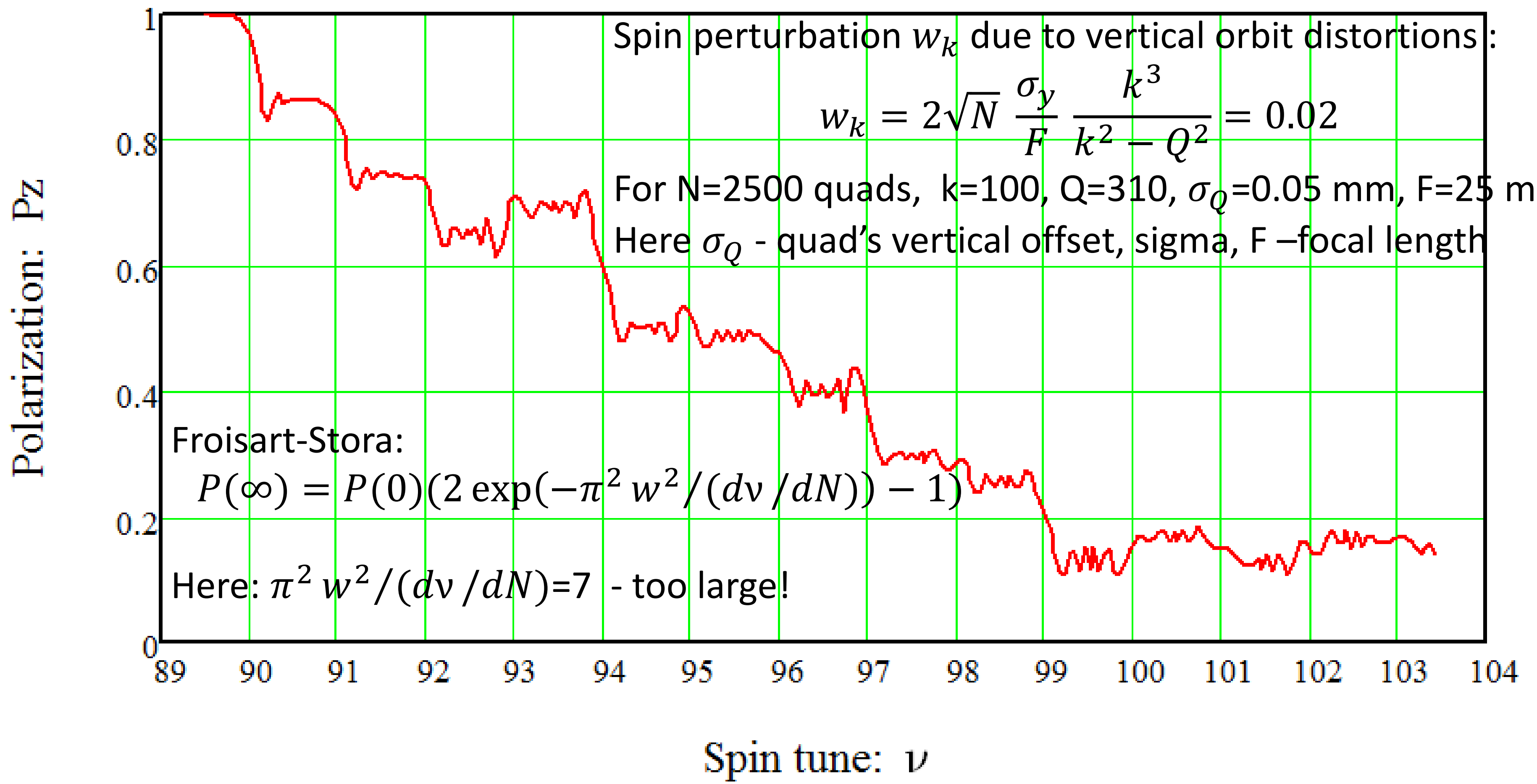
Due to perturbation (w=0.1) the spin precession frequency became shifted to 0.3702 from the ideal 0.3631 value.



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

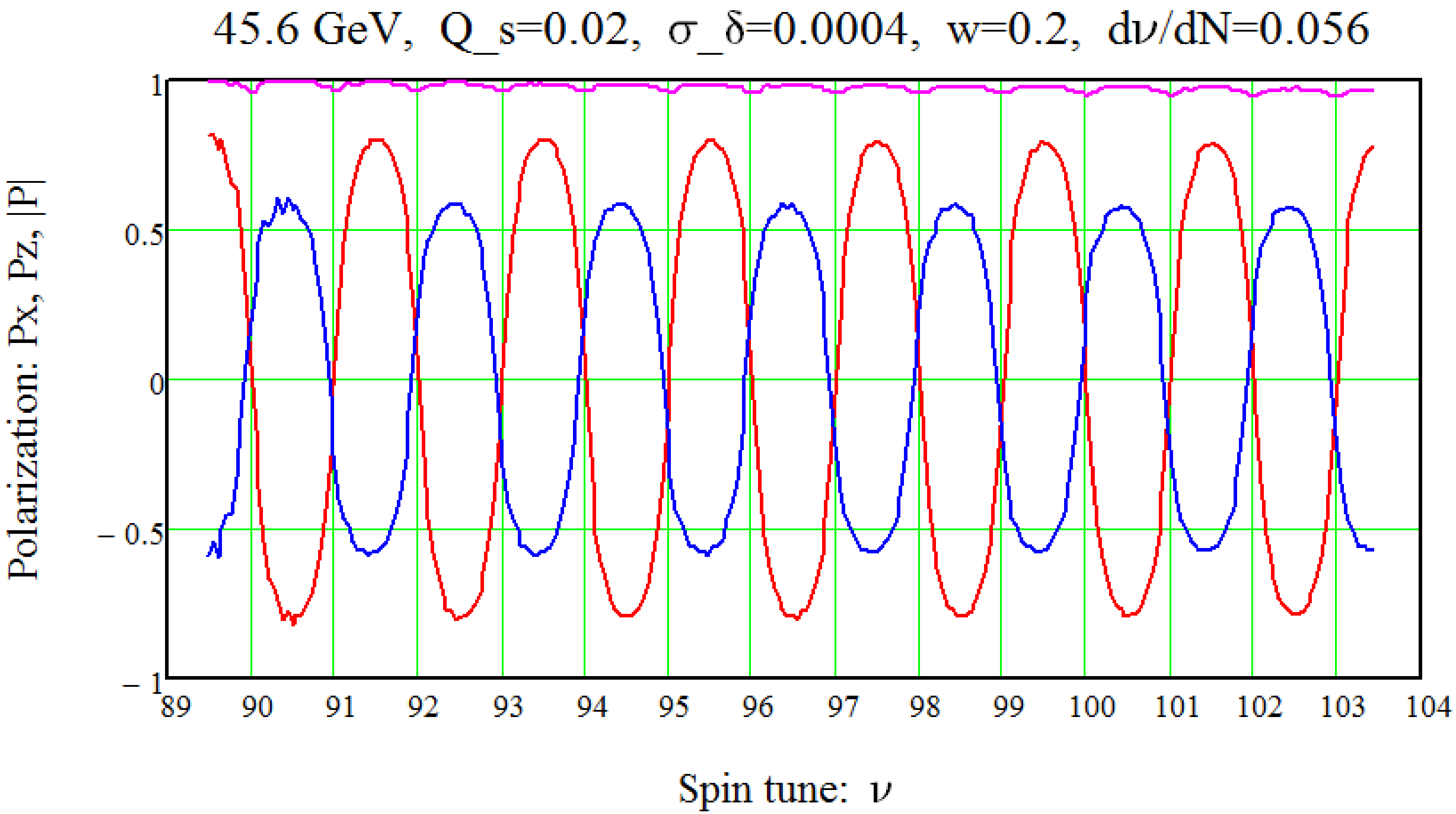
Option-2: Fast acceleration in a booster ring

39-45 GeV, Q_s=0.02, σ_δ=0.0004, w=0.02, dν/dN=0.056



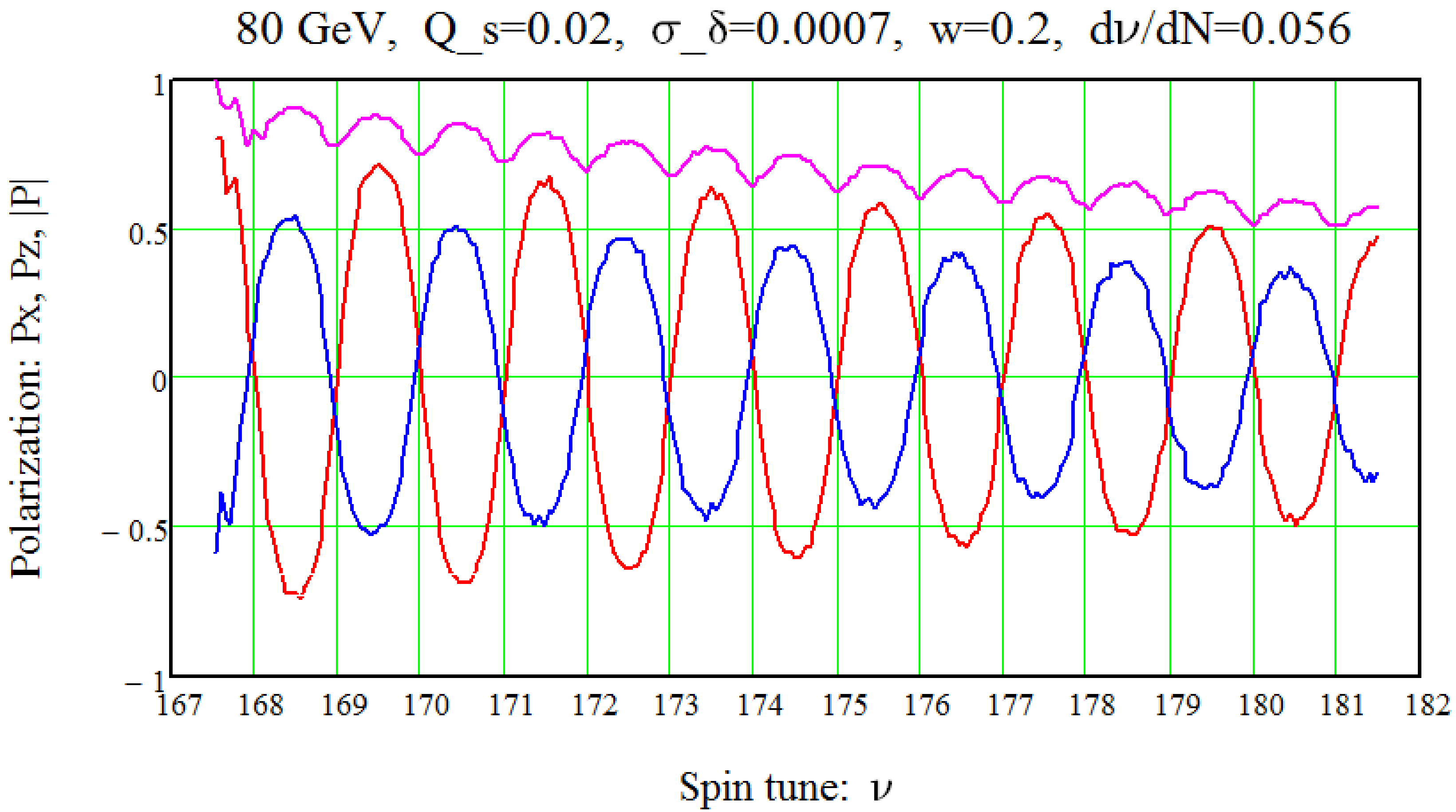
As one can see, the presented here simulation shows very strong depolarization in the FCC-ee booster synchrotron during acceleration with the nominal ramp rate: 25 GeV/ 0.32 s. Besides, we can expect up to 3 times stronger harmonics due to statistical fluctuations.

Option 3: Adiabatic crossing of integers near Z



Beam polarization is well preserved with the use of single Partial Snake for the acceleration in the FCC-ee booster ring. Polarization loss is only 3%, energy ramp rate 25 GeV/0.32 s.
Can use static solenoid with field integral BL=200 T·m. Then, at 20 GeV we will have w=0.5 (full snake!) and w=0.22 at 45.6 GeV. Quads of spin-rotator will ramp to keep $Q_{x,y} = const$.

Option 3: Adiabatic crossing of integers near W



Beam depolarization is now well pronounced. Polarization loss is about 40 %, energy ramp rate 25 GeV/0.32 s (nominal for booster – see talks from Y.Papaphilippou and B.Haerer at FCC-week 2018). Can increase Snake's strength up to w= 0.5. It helps but not very much. Also can benefit from reduction of energy spread, say about 1.5 - 2 times, but how to do this? Meanwhile, option 3 looks feasible even for W in case if 10% polarization level in the end is OK!

Example of 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 only.
Use of high bending field is energetically beneficial to obtain the required polarization degree.

Conclusion

- At Z the longitudinal polarization looks feasible, but some changes in IR lattice are required to place rotators at ϕ=+15 mr from IP.
- At W rotators should be moved to other drifts located at ϕ=+8 mr from IP. Depolarization rate will be roughly the same as without spin rotators.
- In any case fast acceleration of pre-polarized electron and positron beams has to be foreseen. Partial Snake with static solenoids will preserve polarization during ramping.
- Booster lattice design should be adapted for that snake accommodation.

Thank you for your attention!