Progress in Energy Measurements

Ivan Koop for EPOL team,
BINP, 630090 Novosibirsk

7th FCC Physics workshop

LAPP Annecy

01.02.2024

Outline

- Resonance Depolarization (RDP) of pilot polarized bunch to measure average over the circumference beam energy – run takes about 2-5 minutes, repeat every 7-10 min.

- Alternative approach, based on fast spin rotation to the horizontal plane for Free Spin Precession (FSP) frequency measurement - run takes 2-5 seconds + Fourier analysis. Advantage: fast and direct spin tune measurement.

- FSP method requires the Longitudinal Compton Polarimeter (LCP) – relatively simple and cheep. With few such devices can measure the relative phases of spin precession. Veryfication of saw-tooth energy loss model becomes possible!

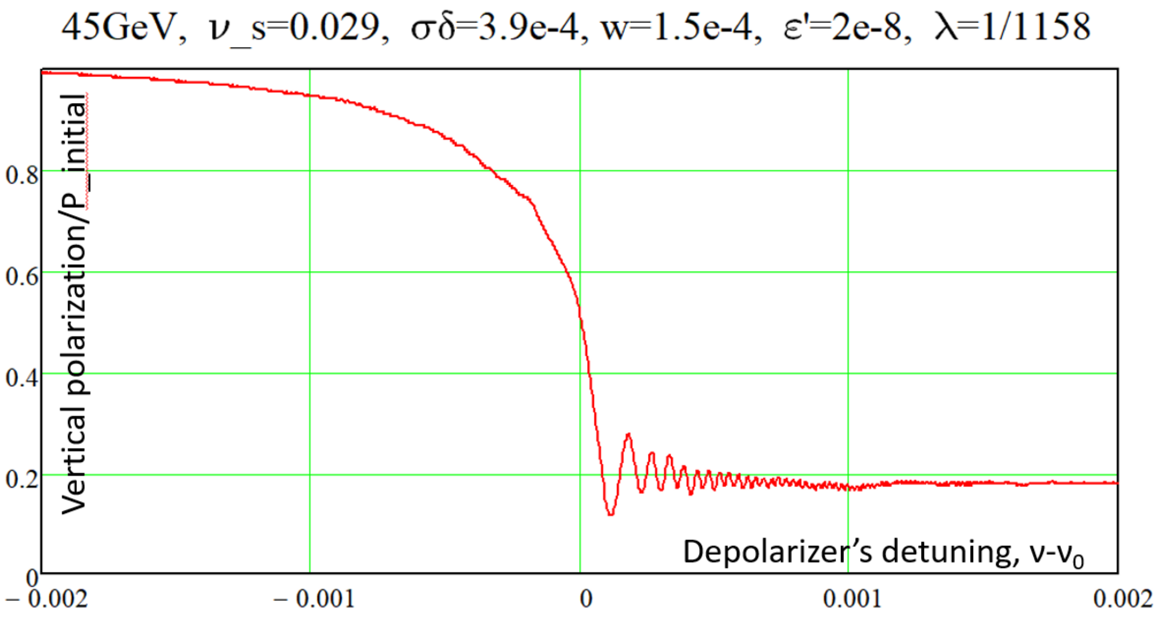
- Quazi continuous RDP of all colliding bunches (to keep the longitudinal component of the polarization below $P\_long < 10^{-5}$)

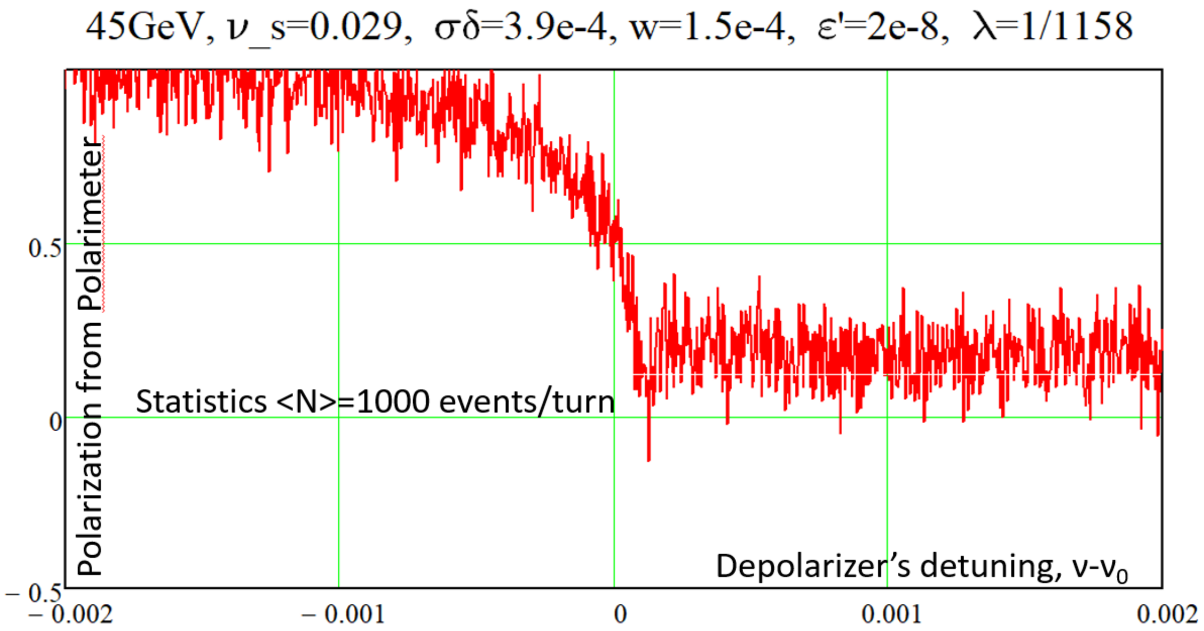
- Local bump spin rotator comprised of two identical transverse AC-field kickers
- Discussion and Conclusion

Baseline scenario for RDP: slow frequency scan.

Relevant parameters: spin tune $\nu_0 = E(GeV)/0.4406486$, the depolarizer's tune $\nu = (f + kf_0)/f_0 = \nu_0 + \varepsilon$, detuning from a resonance by $\varepsilon = \nu - \nu_0$, tune scan rate $\varepsilon' = d\nu/dn$, the strength of a depolarizer (harmonic value) $w = \varphi/2\pi$ - spin rotation by its transverse field in one turn pass through a string of AC-kickers and lenses in between, which comprise the whole depolarizer.

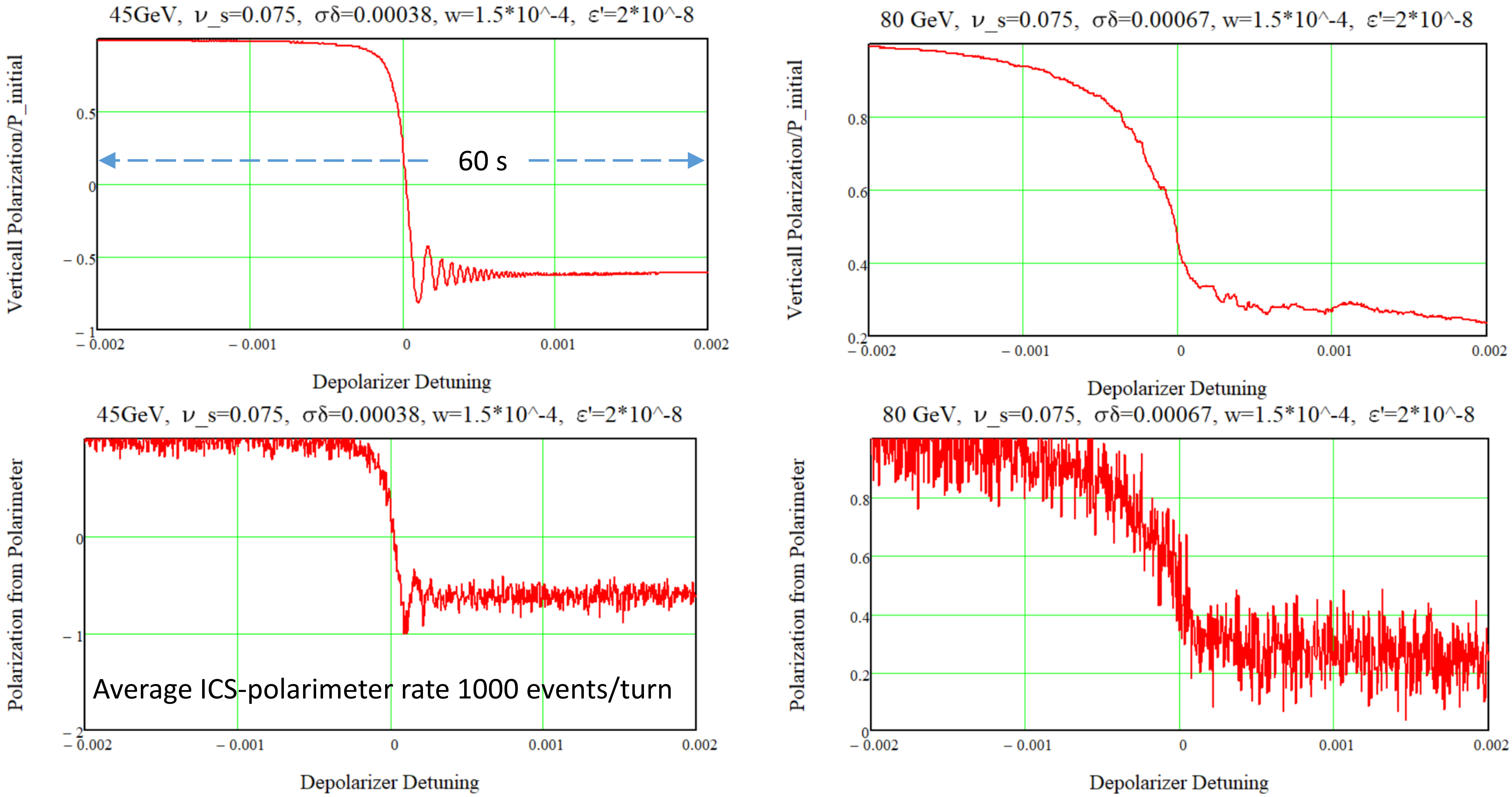
As an example, simulated RDP for 45 GeV with actual beam parameters: small ν_s =0.029





The right plot shows how the statistical noise, which comes from the limited polarimeter's counting rate, smears the depolarization jump.

RDP frequency sweeps with the increased v_s=0.075



Regular RDP procedure: the required depolarizer's strength

At all beam energies the required dimensionless depolarizer's strength is in a range:

$$w = \varphi/2\pi = 10^{-6} \div 10^{-4}$$

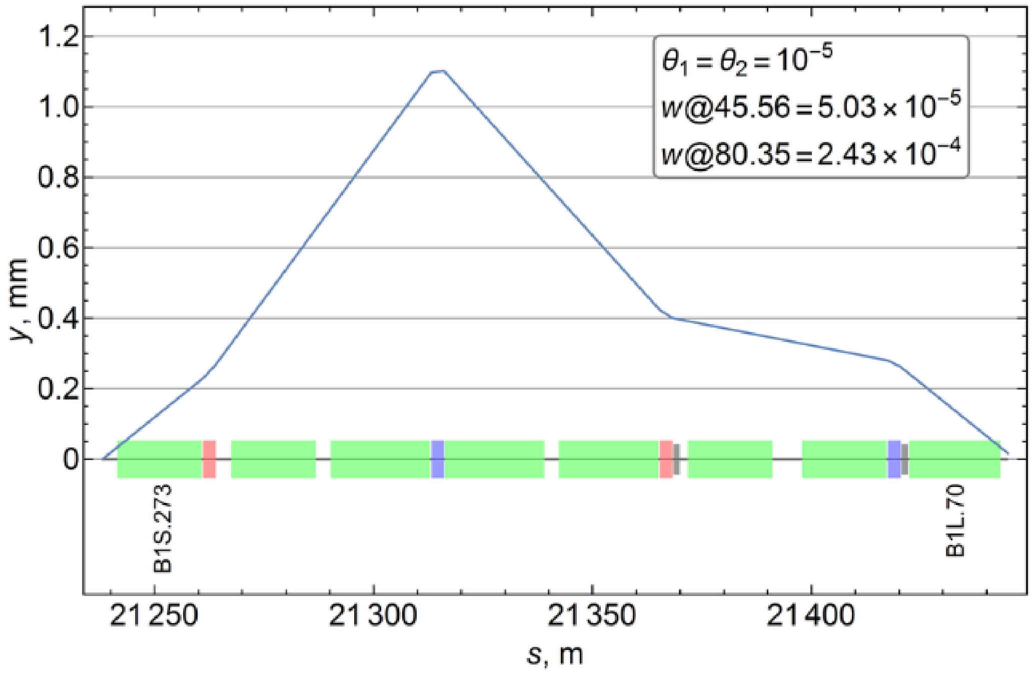
depending on how accurately can we predict the beam energy and then can start a scan closer to the actual spin tune. We remind: each depolarization in everyday life should be carried out in less than 5-10 minutes. This limits the scanning speed from below.

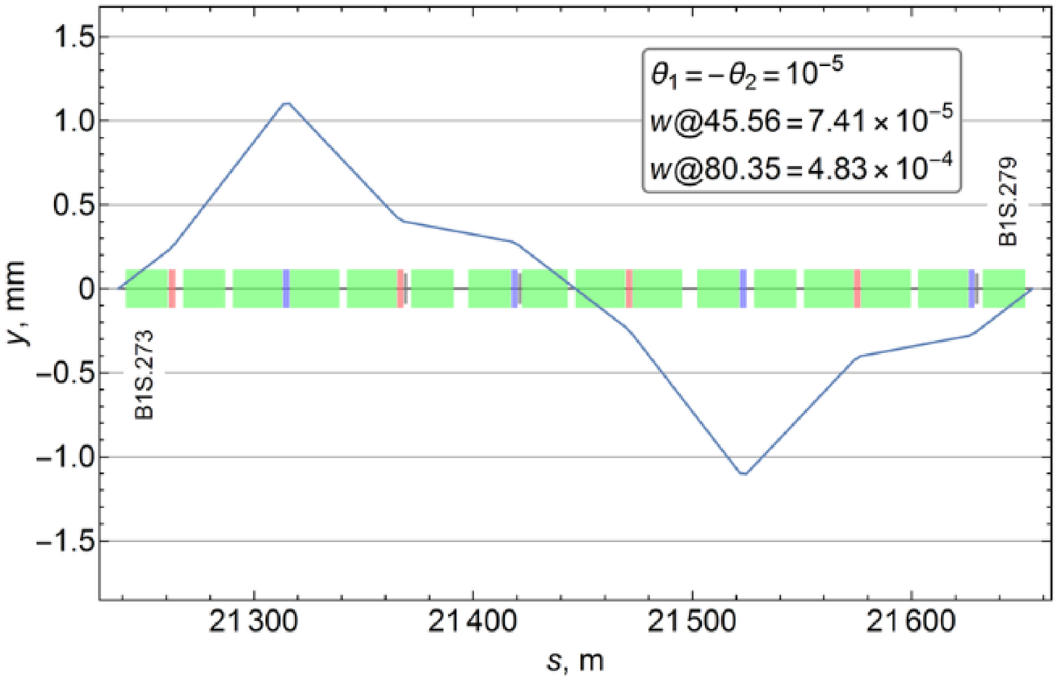
For safety we shall keep a possibility to have a large depolarizer's harmonic: $w \geq 10^{-4}$. But most accurate measurements of the spin tune will be performed at much lower power.

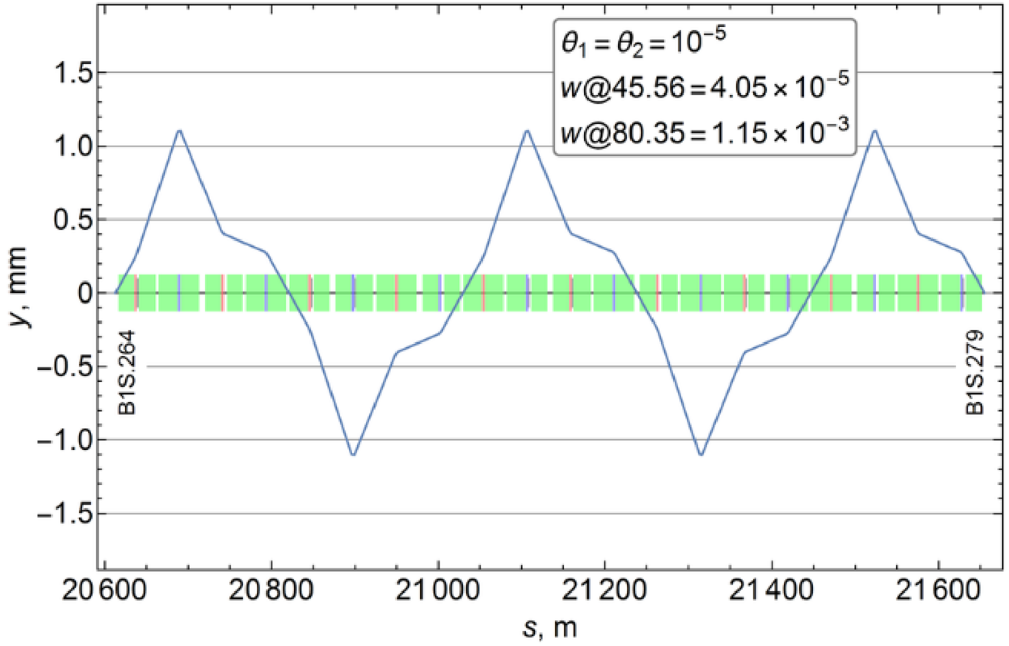
Single depolarizer shakes a beam in the vertical direction. It is undesirable to have any oscillations of the beams at the place of their collision. This requirement can be satisfied only with a local orbit bump, organized by two synchronized kickers (beam shakers).

Such oscillating orbit bumps could be realized in a regular arc lattice, where we have a phase advance of 90^0 per FODO-cell. Bumps can be made with odd or an even number of half-waves between two kickers.

Local vertical orbit bumps (spin rotators) in FCC-ee arc







At 45 GeV a full-wave spin rotator is about 50% more efficient (w=0.000074) than a half-wave spin rotator (w=0.000050).

At 80 GeV, with the same kick angles $\theta_{1,2}$, a half-wave spin rotator is about 45 times more effective than at 45 GeV. This is thanks to about 2 times larger spin rotation angle by the AC-kicks itself, as well as larger spin rotation angles in the horizontal bends.

The forced oscillation amplitude for $\theta_{1,2} = \pm 10^{-5}$ is about 1 mm inside the local orbit bump region and is kept zero outside. Shall prove the DA!

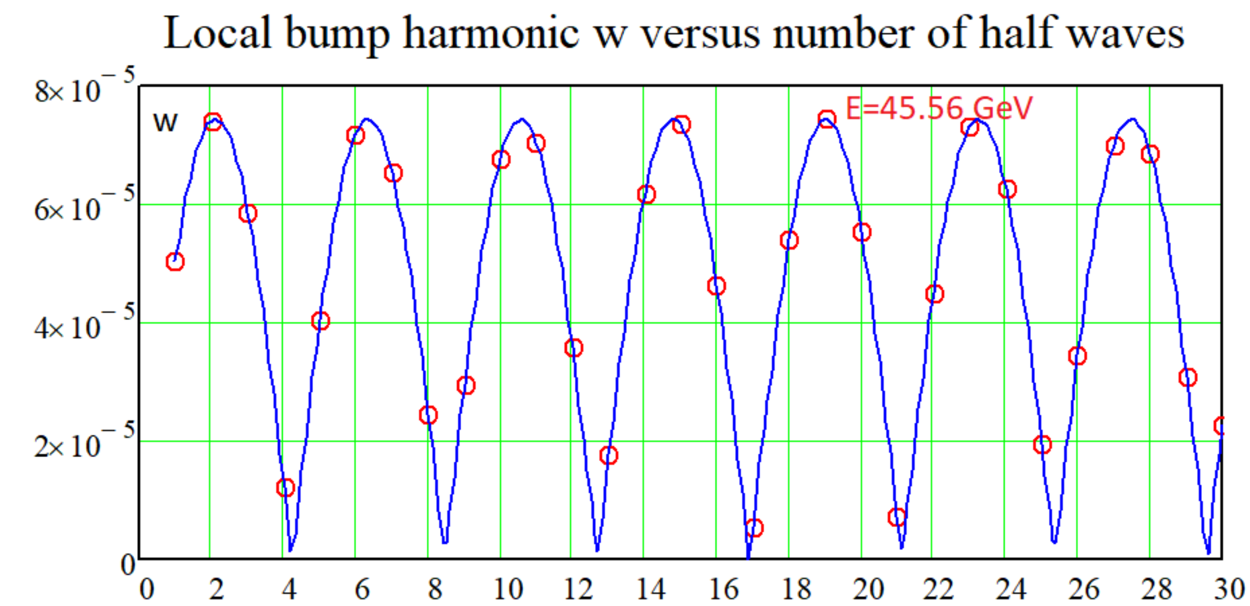
Algorithm to calculate w for the local vertical orbit bumps

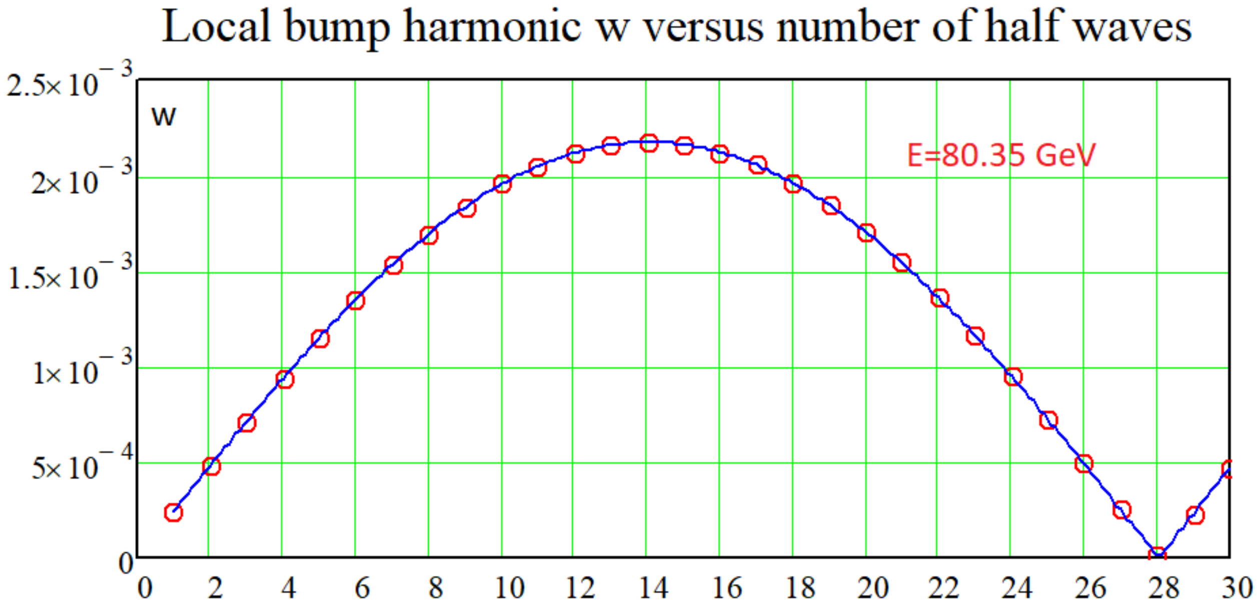
The effective harmonic value w of a local bump spin rotator is just a sum of $\nu_0\alpha_m$ - spin rotations by the M kickers or quads around the x-axis. Each kick is included in the final sum with a weighting factor $\eta_m = e^{i\nu_0\varphi_m}$:

$$w = \frac{1}{4\pi}\sum_{m=1}^{M}\nu_0\alpha_m \cdot \eta_m$$

Where ν_0 is a spin tune, and φ_m is the total horizontal bend angle starting from the first kick.

Harmonic value at Z and at W versus the number of half waves





A half-wave bump is the shortest. Longer spin rotators consisting of N π-bumps could provide a greater value of the harmonic of the depolarizer. Their strength can be calculated as a sum of geometric progression:

$$w_N = w_1 \left| \frac{1 - (-e^{i\nu\cdot\Delta\varphi_M})^N}{1 + e^{i\nu\cdot\Delta\varphi_M}} \right|$$

At Z the spin phase advance $\nu \cdot \Delta\varphi_M = 1.655$ per one half-wave bump is small and increase of N is not efficient.

On the contrary, at W the spin phase advance $\nu \cdot \Delta\varphi_M = 2.918$ per one half-wave arc section is close to its optimal value π, and w grows almost linearly with increasing N. Its optimal value would be N=14. Then $w = 2.2 \cdot 10^{-3}$ for kick angles $\theta_{1,2} = \pm 10^{-5}$.

Remind: only two AC-magnets are needed for the whole N half-waves depolarizer!

Why traveling wave depolarizer, but not AC-solenoid?

A traveling wave depolarizer, based on the use of a strip line, is capable of generating the short pulses necessary to depolarize single bunch in a train.

With the solenoid such a game does not work! Very large inductive load for the AC-generator! ($f \approx 1.5\ kHz$)

Another argument: the transverse kick angle of an orbit would be amplified for spin rotation at least by a factor $\nu_0 \approx 100$ at Z and few times more at WW energy regions.

AC solenoids can be used to continuously depolarize colliding bunches, but the required electrical power, seems, is too high.

In this report we focus our attention on the traveling wave approach.

Depolarizer parameters for RDP of a single bunch

The desired harmonic of the depolarizer $w = 1.4 \cdot 10^{-4}$.
At Z two full-wave local bumps are required to limit the beam deflection inside a bump by +- 1 mm.

Then at Z-energy $\theta_{kick} = 1 \cdot 10^{-5}$ - kick angle should be provided by each AC-kicker.

$BR = 150\ T \cdot m\,, \qquad El = Bl = 0.5 \cdot \theta_{kick} \cdot BR = 7.5 \cdot 10^{-4}\ T \cdot m$

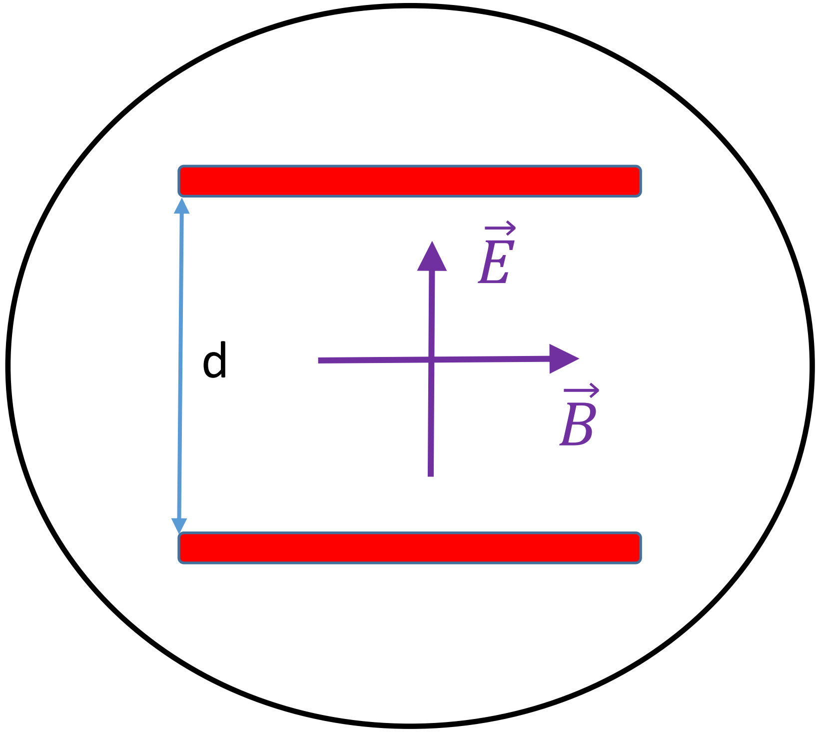
$l = 2.5\ m, \qquad d = 2\ cm, \qquad B = 3\ Gs, \qquad E = 900\ \ V/cm\,,$

$U = 0.5 \cdot E \cdot d = 900\ V, \qquad P_{pulse} = 0.5 \cdot U^2/Z_{Line} = 8100\ W,$

$\langle P \rangle = P_{pulse} \cdot \Delta t/T = 8100 \cdot 10\ ns/320\ mks = 250\ mW$ - during a pulse, in case of RDP of a single bunch!

Technically looks feasible? Parameters could be relaxed, if the distance between plates could be made smaller: $d = 1\ cm$?

Strip Line sketch:



Depolarizer parameters for free precession mode at Z

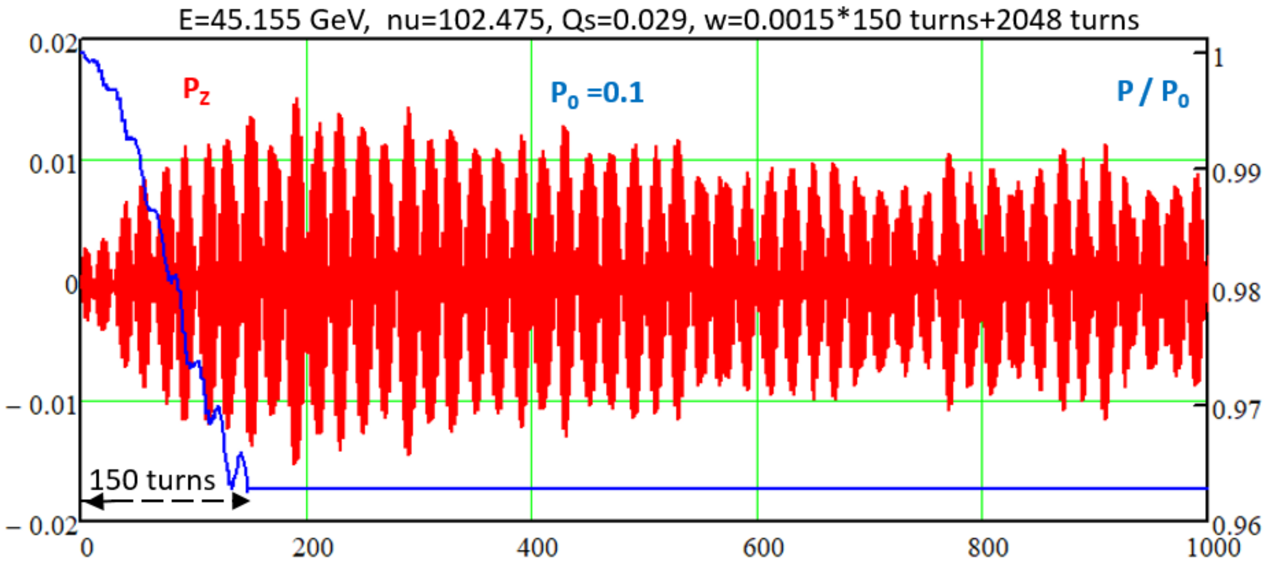
For free precession the desired harmonic of the depolarizer should be increased up to $w = 0.0015$ at 45 GeV (10 times as higher compared with RDP) and about up to $w = 0.003$ at 80 GeV (with N=14 half-waves bump it is easier than at Z) . Too low $\nu_s = 0.0288$ (with last RF-parameters) leads to too large modulation index of the synchrotron tune:

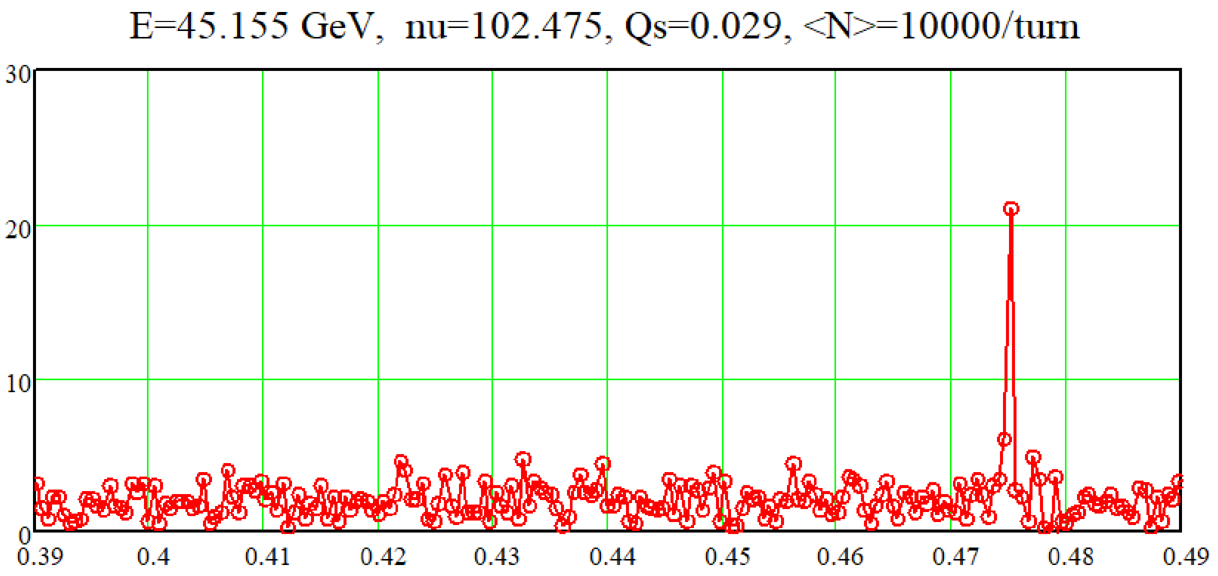
$$\xi = \nu_0 \sigma_\delta / \nu_s = 1.85$$

This makes problematic the spin rotation by a flipper. Only a small part (only a few percent!) of spins deviates from the vertical direction and begins precess around the vertical axis.

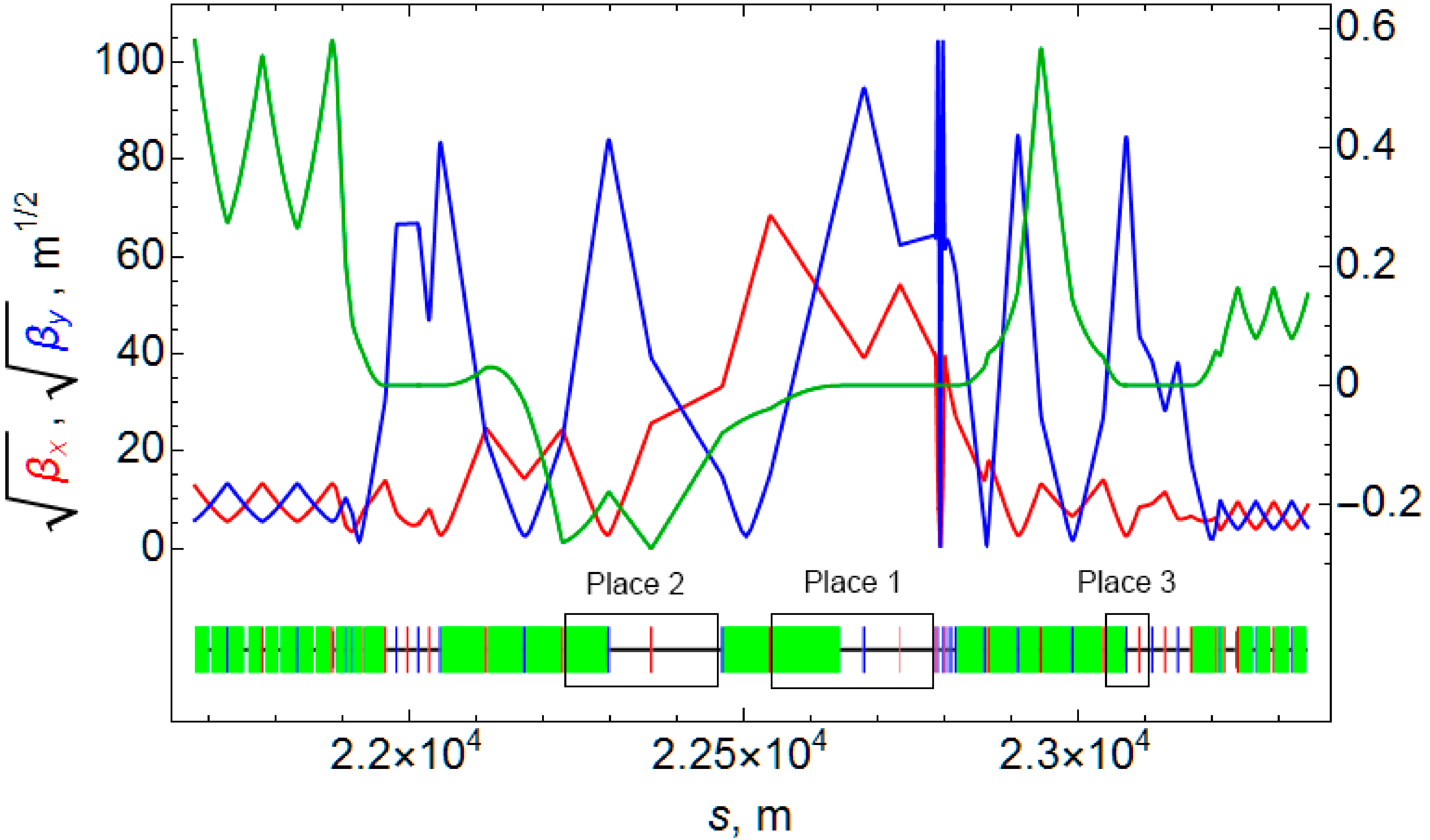
The required number of local bumps should be increased to 5-20, depending on the actual limitations of DA.

Larger number of dipoles between two AC-kickers would help very much! Means two times longer cell in arc?

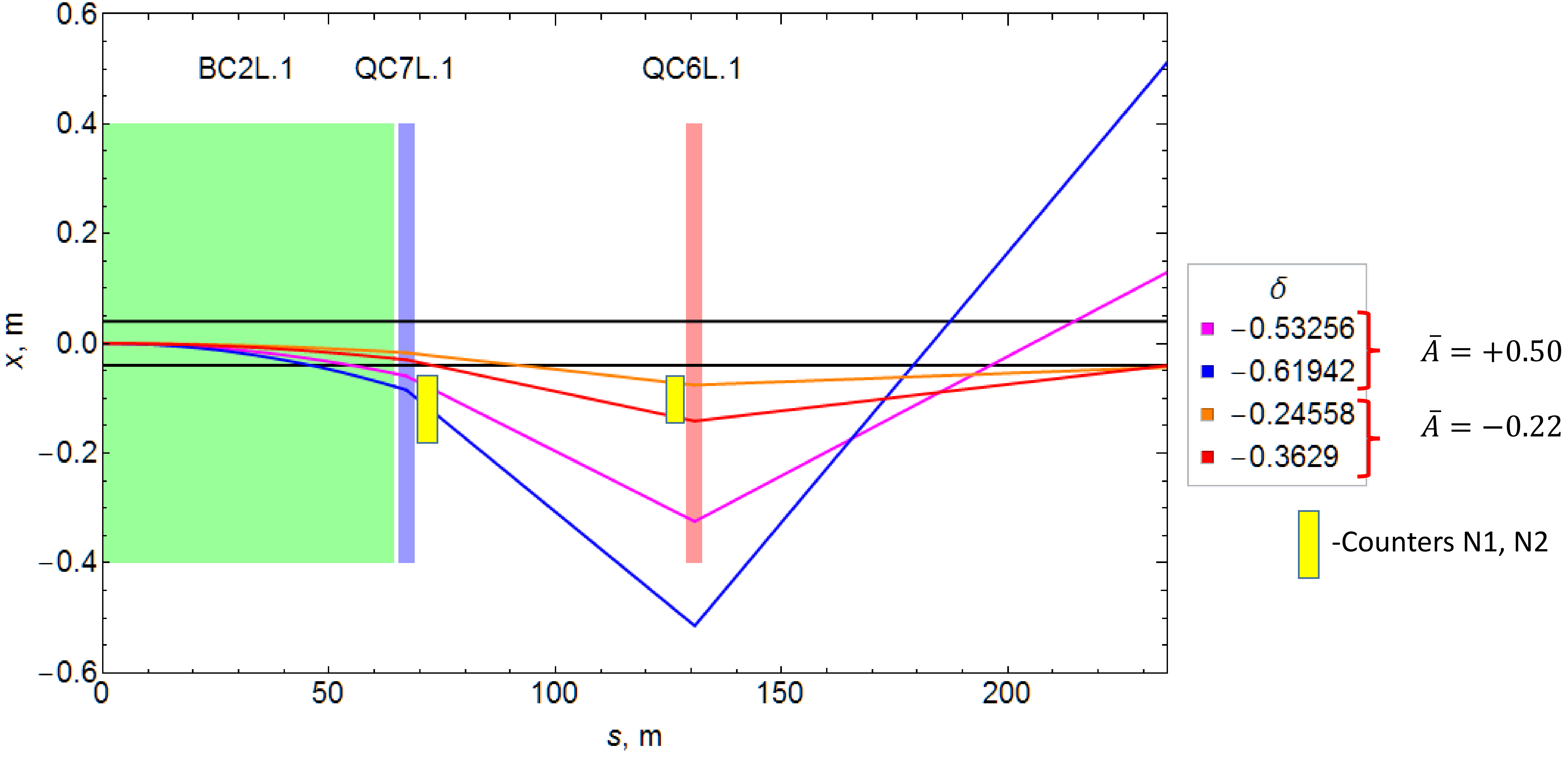




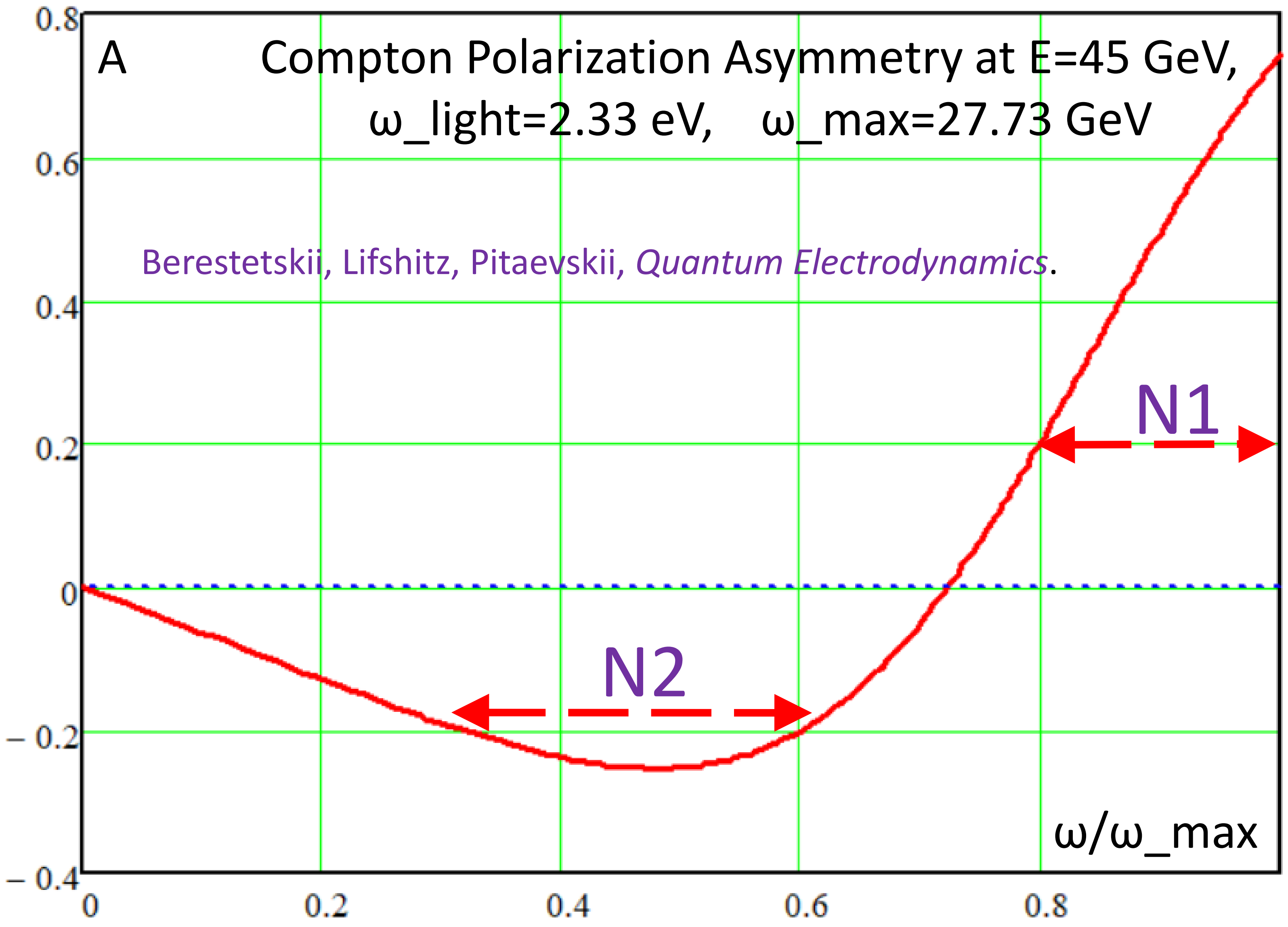
Possible longitudinal polarimeter locations in FCC-ee



Trajectories with different energy losses at E=45.6 GeV, place 2:



Compton polarimeter asymmetry to longitudinal polarization at Z

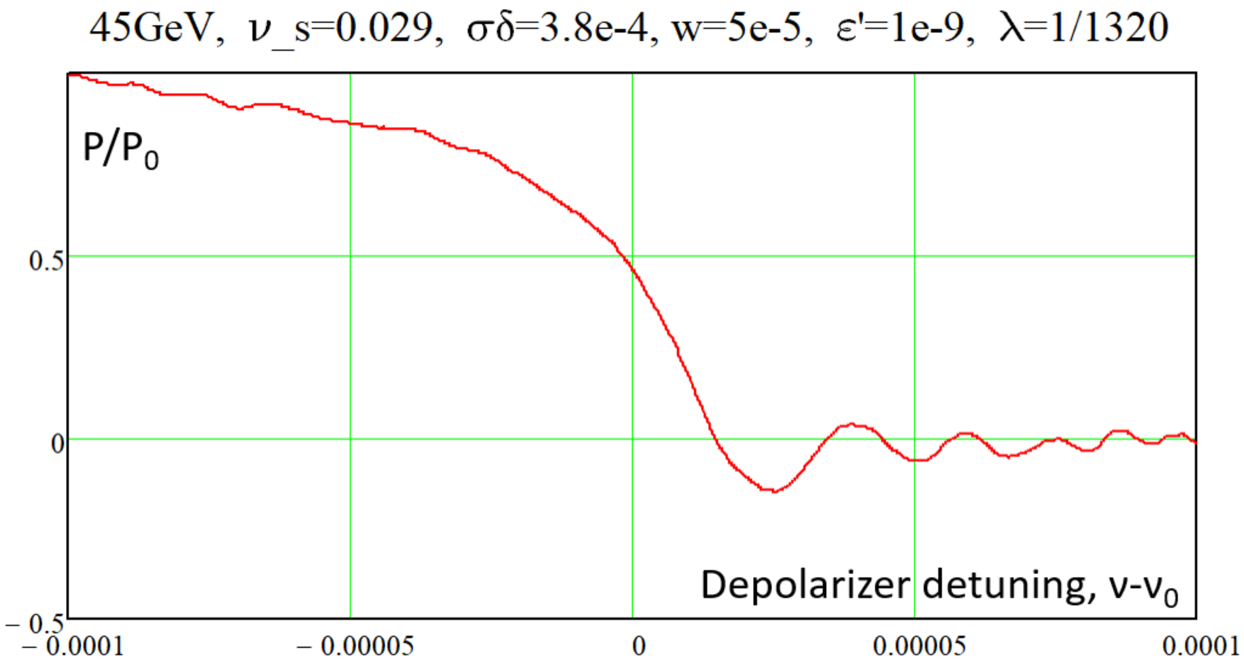


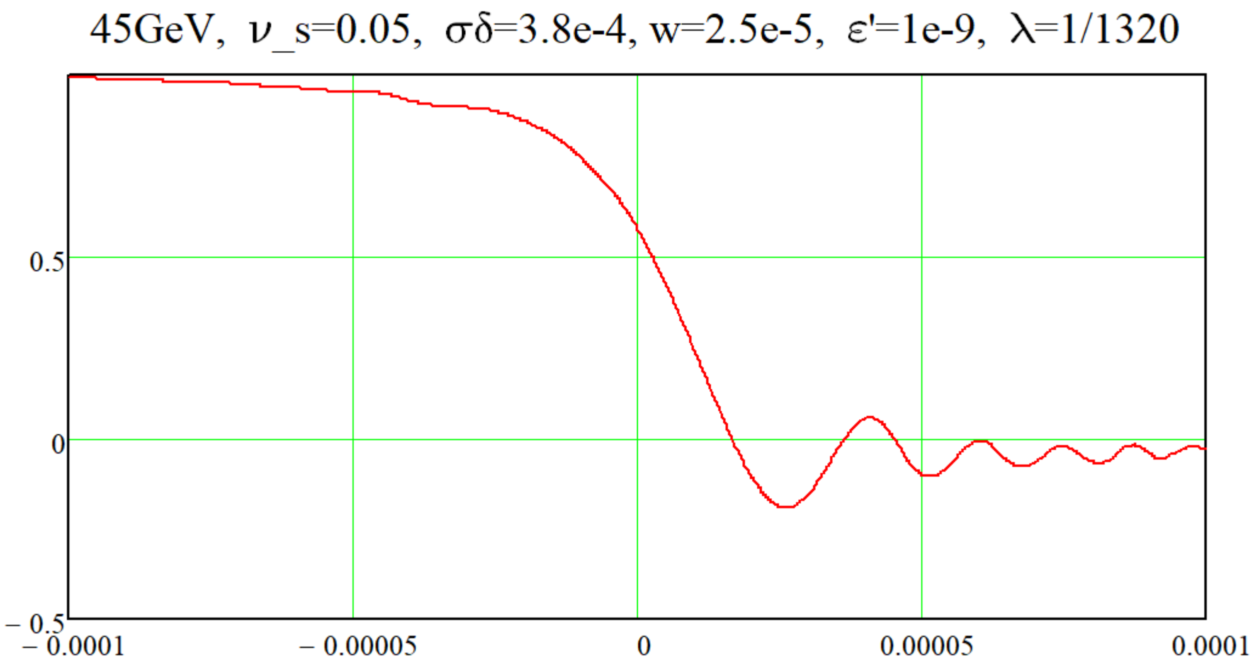
In case of coherent spin precession we can explore large asymmetry *A* to the longitudinal spin component of the ICS cross-section, selecting events from two regions: $\omega/\omega_{max} > 0.8$ (N1) and $0.3 < \omega/\omega_{max} < 0.6$ (N2). Then do FFT analysis of a signal: (N1-N2)/(N1+N2), modulated by spin precession.

Parameters for continuous depolarization of the colliding bunches

For continuous beam depolarization the strength of a depolarizer could be decreased down to $w = 0.00005$ at 45 GeV. At the same time, it is assumed that we know the position of the resonance very well and do slow scan of the resonance zone, passing it in about 80 seconds. An examples of such a scan are shown below. For larger synchrotron tune we can use weaker depolarizer.

Due to the continuous mode, the power dissipation in the strip lines increases dramatically. Some cooling of the strip line plates should be provided.





Conclusion

The concept of a local orbit bump depolarizer looks feasible. The electrical circuit of the depolarizer must be developed. Commercial broadband amplifiers show, in principle, the required parameters.

For beam energy of 45 GeV, the optimal length of such a device is the full-wave part of an arc section. For continuous RDP of colliding bunches few such depolarizers are needed, or the horizontal tune Qx should be made about 2 times lower. This also would help to increase the synchrotron tune to ν_s =0.05 or even higher values to make smaller the synchrotron modulation index – resulting in more stable and accurate RDP/FSP.

The single AC-kicker is a strip line about 2.5 meters long. A gap between the plates is about 1-2 cm. The applied voltage in traveling wave is about 900 V.

The generator of the depolarizer should produce a sequence of short pulses of variable amplitude, lasting about 20 ns, spaced by one revolution period or by the time distance between the bunches. For continuous operation, the generator signal could be just a sine wave.

An advantage of FSP – the orbit is completely undisturbed during the precession frequency measurement procedure. The design of the required for this of the longitudinal polarimeter should be worked out.

Thank you for your attention!