High energy polarized electrons

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Outline

- Motivations
- Radiative polarization
- Solenoid type spin rotators
- Acceleration of polarized beams in a booster synchrotron with Siberian snakes
- Longitudinal polarization at Z-peak
- Energy calibration
- Conclusion

Motivations

TLEP-FCC-ee; CEPC

- highest possible luminosity for a wide physics program ranging from the Z pole to the $t\bar{t}$ production threshold
  - *beam energy range from 45 GeV to 175 GeV*
- main physics programs / energies:
  - *Z (45.5 GeV): Z pole, 'TeraZ' and high precision M_Z & Γ_Z,*
  - *W (80 GeV): W pair production threshold,*
  - *H (120 GeV): ZH production (maximum rate of H's),*
  - *t (175 GeV): $t\bar{t}$ threshold*
- some polarization up to ≥80 GeV for beam energy calibration

longitudinal polarization at Z

Radiative polarization

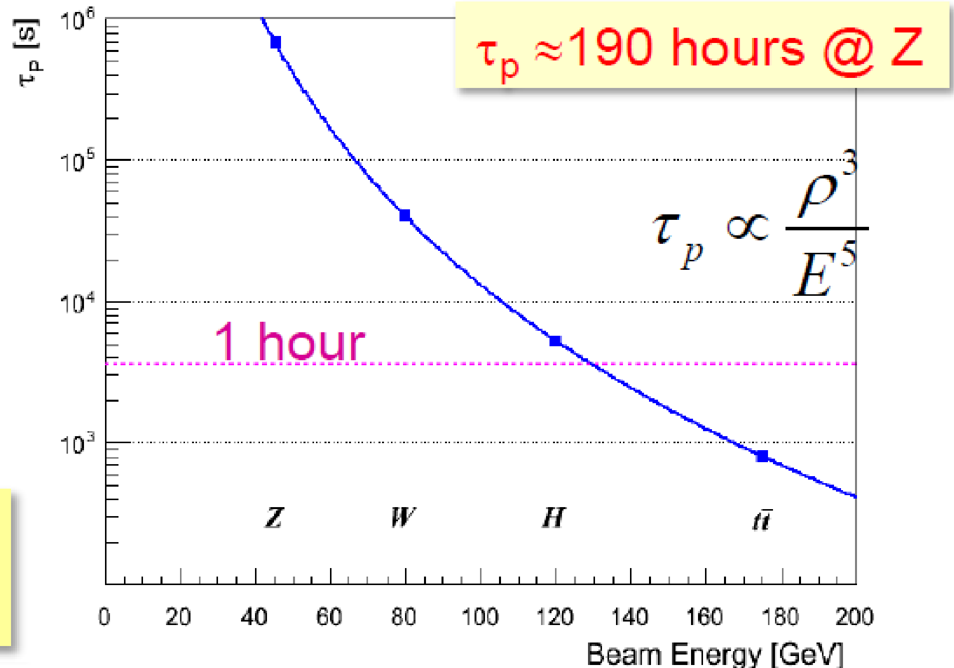
transverse polarization build-up (Sokolov-Ternov) is slow at *FCC-ee* (large bending radius ρ)

build-up is ~40 times slower than at LEP

wigglers may lower τ_p to ~12 h, limited by $\sigma_E \leq$ 60 MeV and power

due to power loss the wigglers can only be used to pre-polarize some bunches (before main injection)

≈ OK for energy calibration (few % P sufficient)

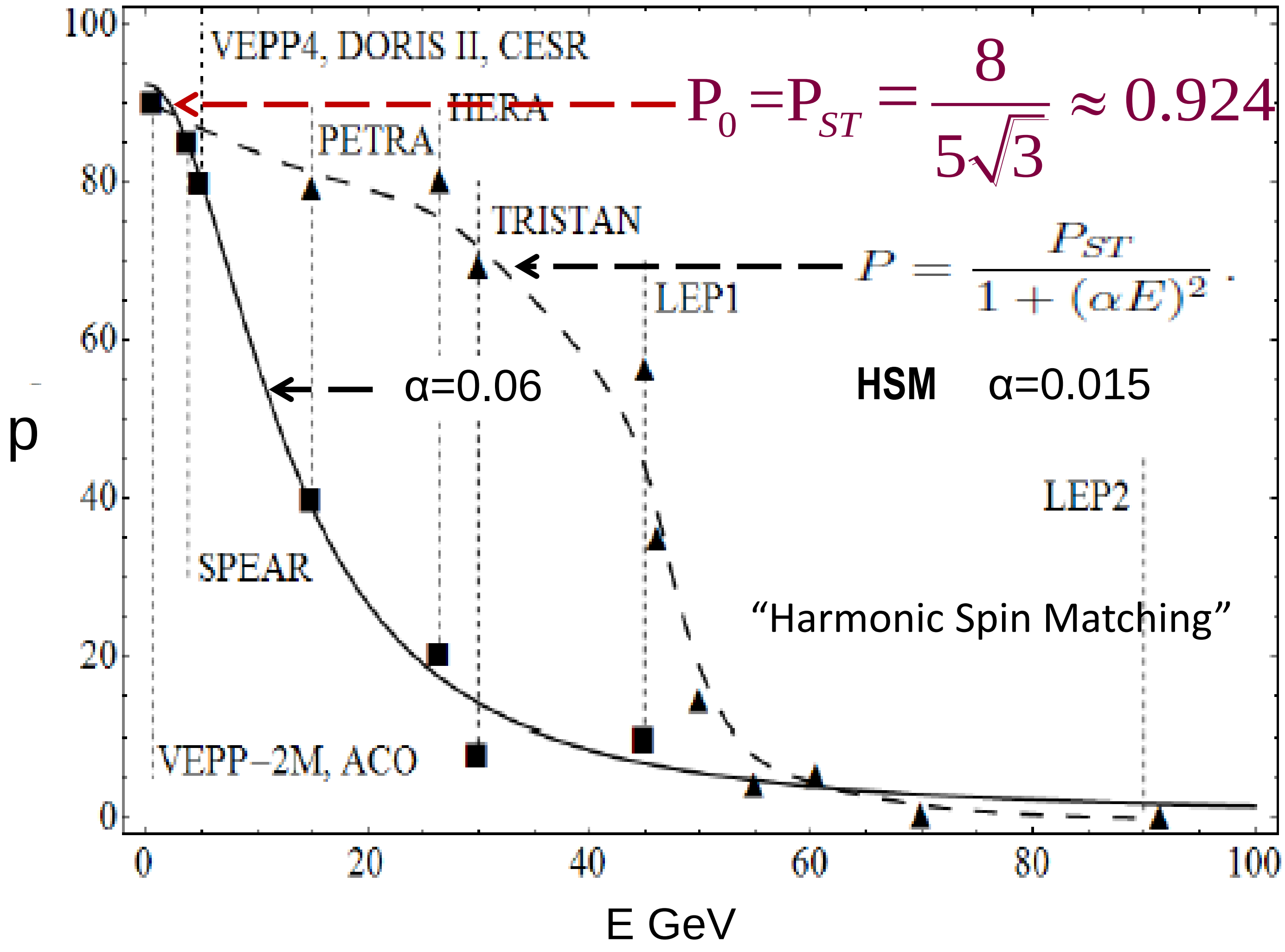


<u>longitudinal polarization</u>: levels of ≥ 40% required on both beams; excellent resonant compensation is needed

$$P_{\rm avg} = \frac{1}{N_0}\int_0^{\infty}\frac{N_0}{\tau_\ell}e^{-t/\tau_\ell}P_0(1-e^{-t/\tau_p})\,dt = \frac{P_0}{1+(\tau_p/\tau_\ell)}$$

Radiative polarization (plus sight)

R. Assmann *et al.*, *Nucl. Phys. B Proc. Suppl.* 109 17–31 (2002).

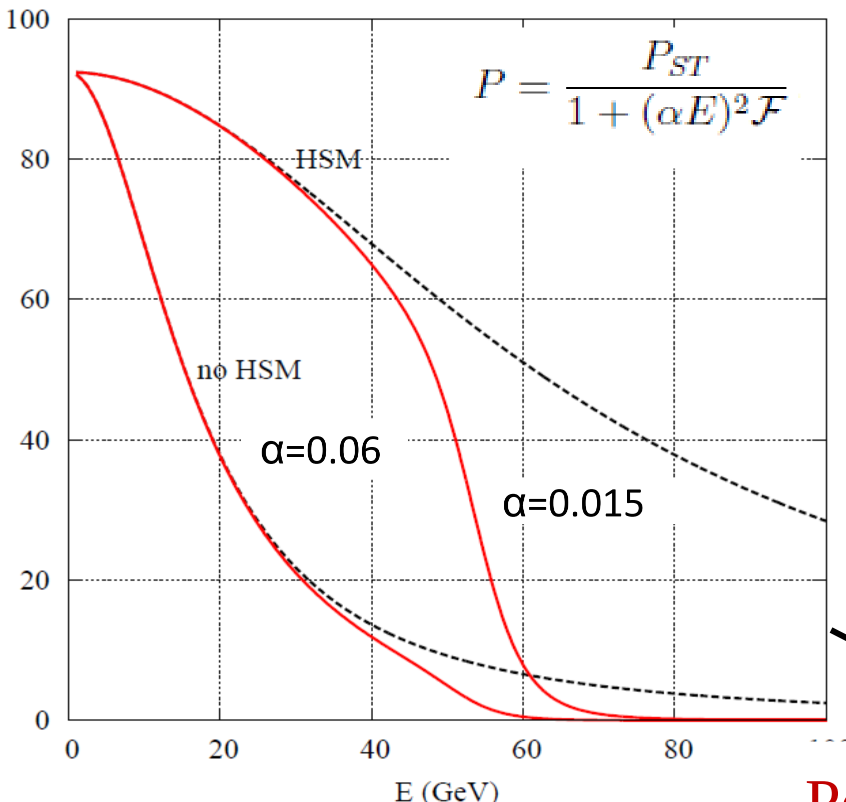


Depolarization enhancement due to side bands

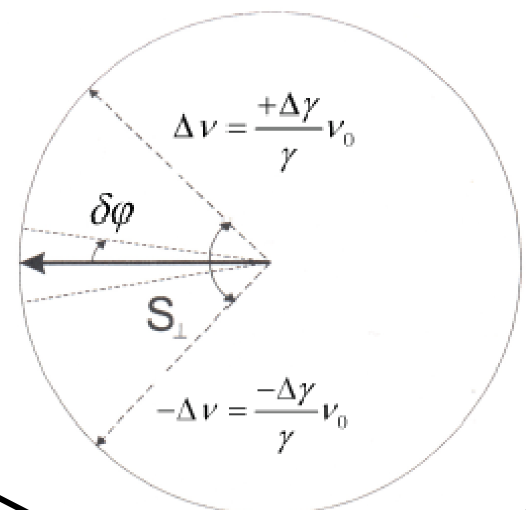
Ya.Derbenev, A.Kondratenko, A.Skrinsky, Particle Accelerators **9** (1979) 247.

Modulation index: $\chi = \dfrac{\nu_0 \sigma_\gamma}{\nu_\gamma}$

$$\left\langle K^3 \left(\gamma \frac{\partial \vec{n}}{\partial \gamma}\right)^2 \right\rangle / \left\langle K^3 \right\rangle = \nu_0^2 \sum_{k,m} \frac{w_k^2 \cdot I_m(\chi^2/2)\, e^{-\chi^2/2}}{\left[(k - \bar{\nu} - m\nu_\gamma^2) - \nu_\gamma^2\right]^2}$$



Synchrotron oscillations
("top view")



Spin diffusion
due to quantum
fluctuations:

Drift spin phase
during one period
of synchrotron osc.

$$\Delta\phi \approx \frac{\nu_0^2 \sigma_\gamma^2}{\nu_\gamma^3 \tau_0} \sim \gamma^8$$

Polarization shot-stop

LEP 70 GeV; FCC-ee 100 GeV $\chi \sim 1; \quad \Delta\phi \sim 1$

Spin response functions (HSM?)

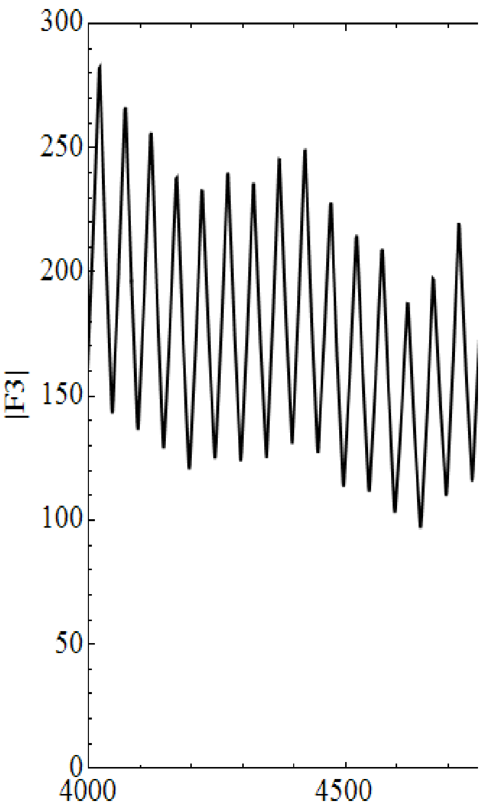
V.I.Ptitsin, Yu.M.Shatunov, S.R.Mane, NIM A608 (2009) 225.

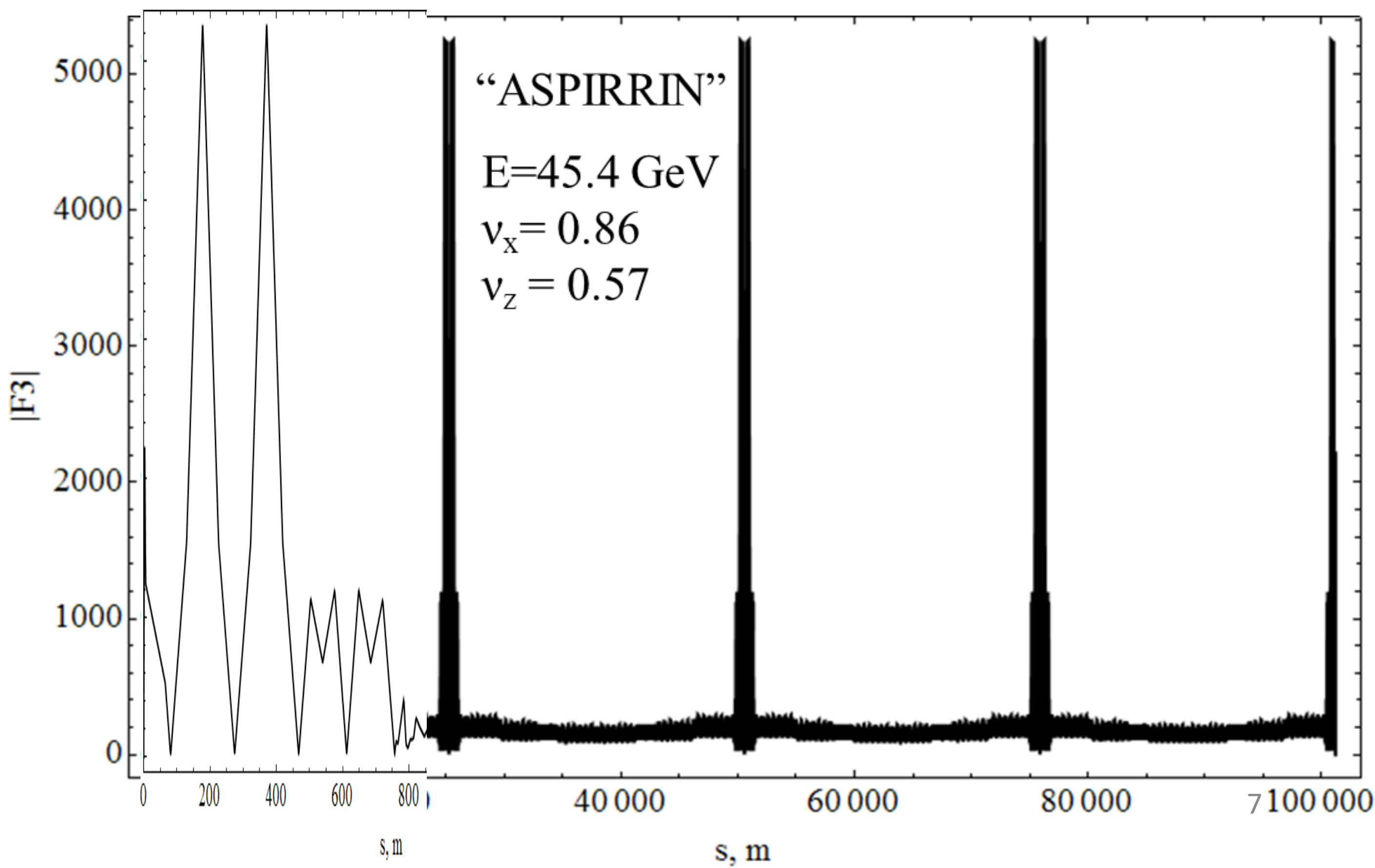
$$\frac{\partial \mathbf{n}}{\partial p_x} = \Re e\left\{i[-(1+\nu_0)\eta_z + F_1]\boldsymbol{\eta}^*\right\}\ ; \quad \frac{\partial \mathbf{n}}{\partial p_z} = \Re e\left\{i[-(1+\nu_0)\eta_x + F_3]\boldsymbol{\eta}^*\right\}\ ;$$

$|F_3| \sim \nu_0^2$

$|F_3| \sim (\nu_0 - \nu_z)^{-1}$

$$\mathbf{d} = \gamma \frac{\partial \mathbf{n}}{\partial \gamma} = \Re e(iF_5\boldsymbol{\eta}^*) \qquad F_5 = \frac{i}{e^{i\nu 2\pi} - 1}\int_{\theta}^{\theta+2\pi}\left[K_z(\nu_0\eta_z - F_1) + K_x(\nu_0\eta_x - F_3) - K_y\eta_y\right]d\theta.$$



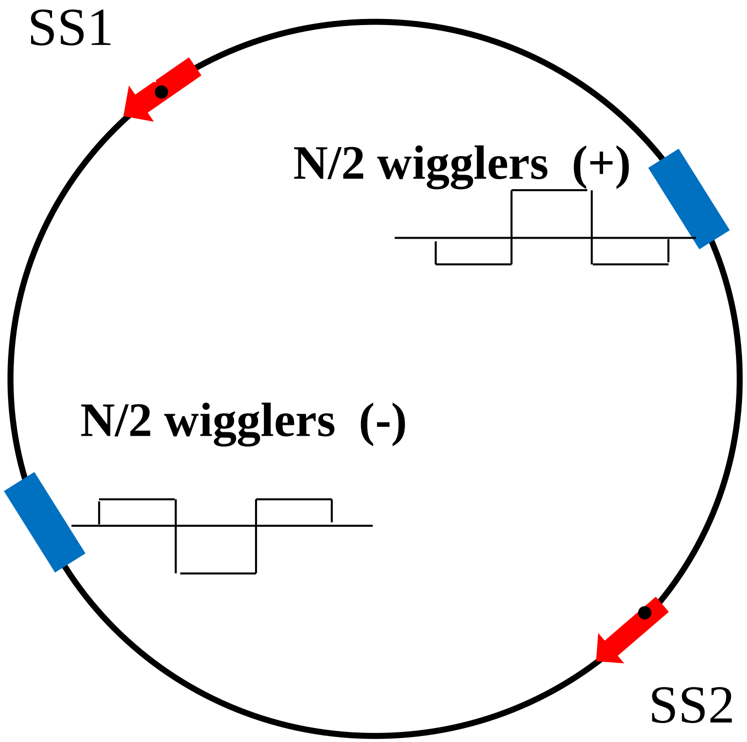


Radiative polarization with Siberian snakes

S.Mane arXiv:1406.0561v1 [physics.acc-ph] 3 Jun 2014

N asymmetrical wigglers

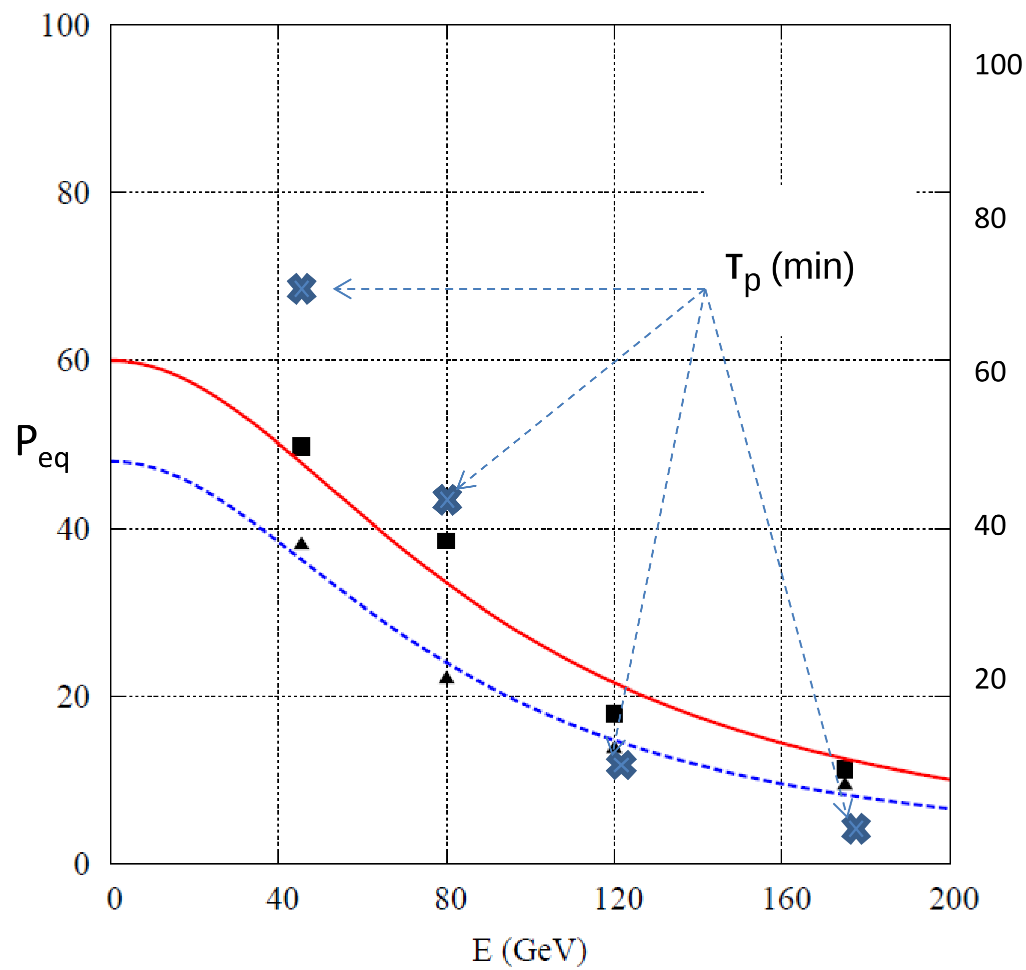
N=28 ---- 5



Snake asymmetry

1→2=f L; 2→1=(1-f)L

Spin tune $\nu = \nu_o(1-2f)$



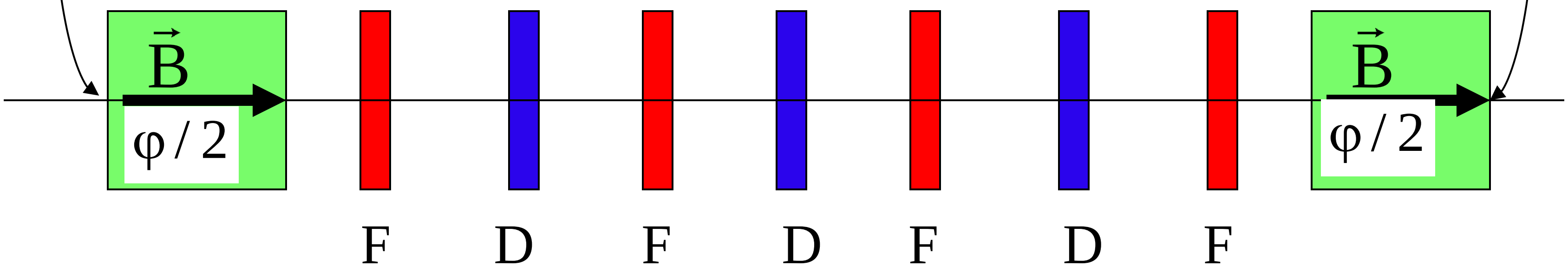
Spin transparent rotator with solenoids

For decoupling should be $T_x = -T_y$ ← Litvinenko, Zholentz, 1980

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

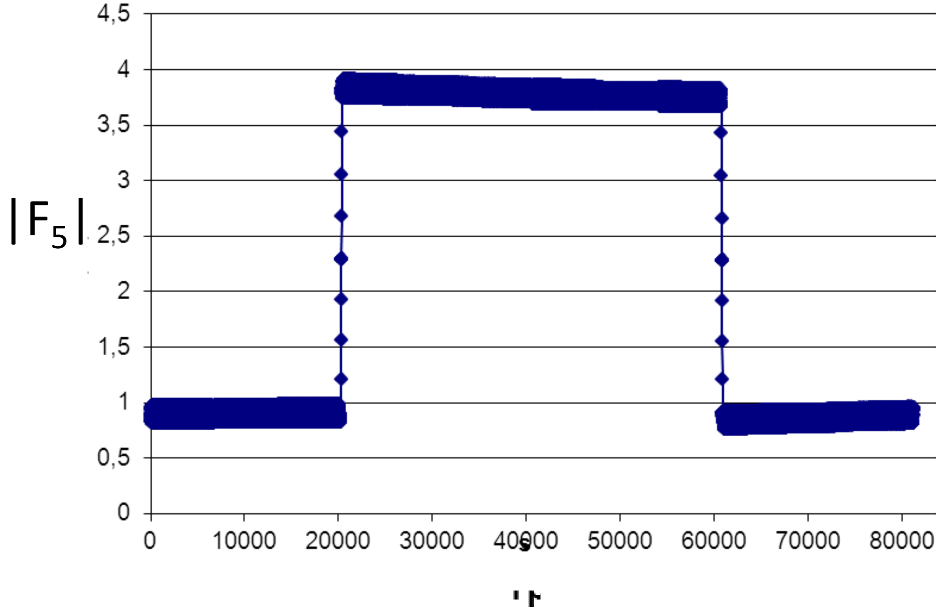
for the spin transparency!
(Koop et al., SPIN2006)

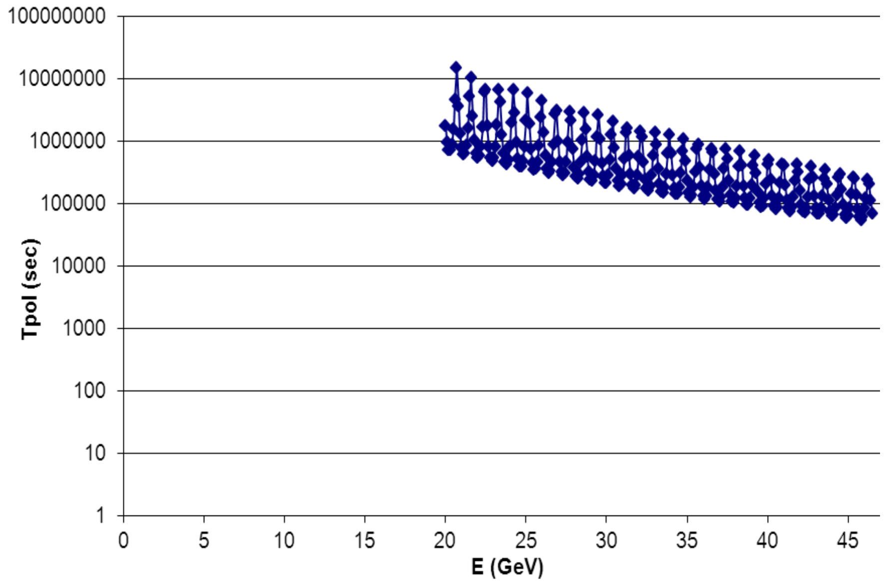
$r = pc/eB$

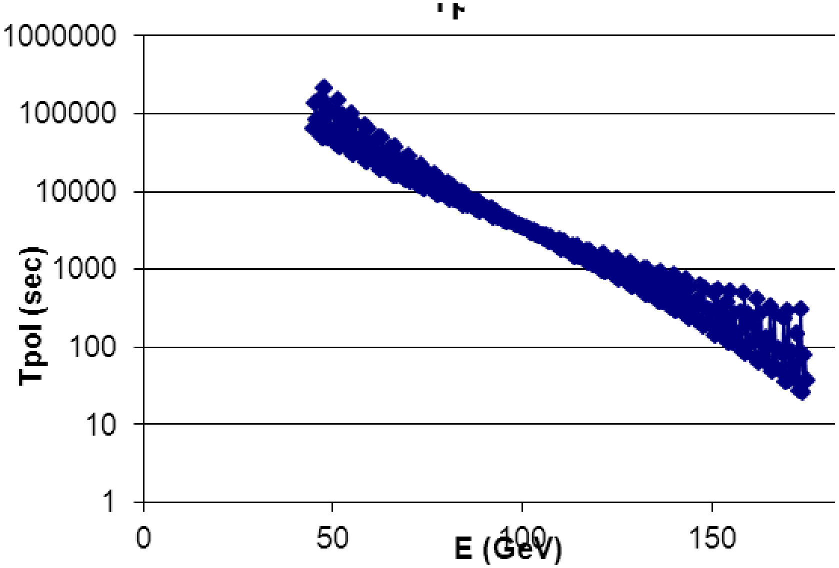


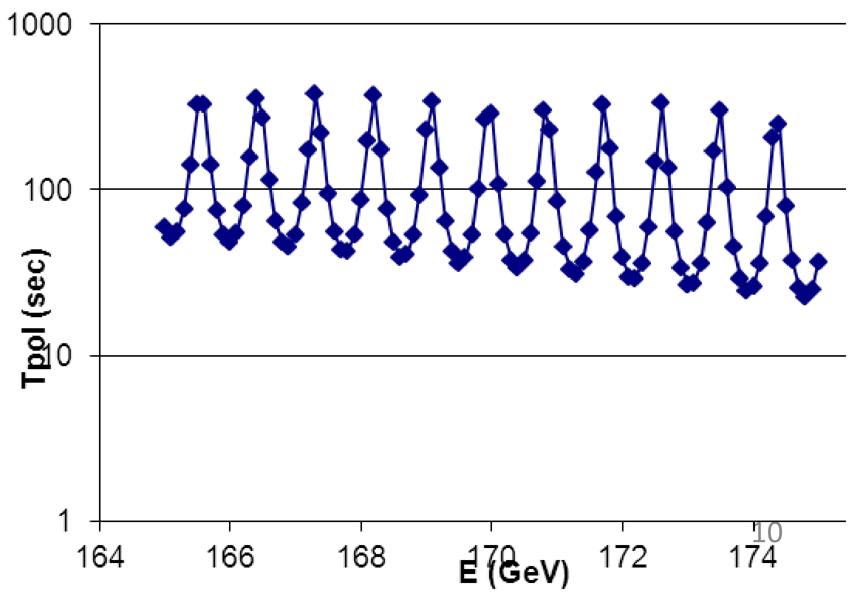
Two solenoids, each L=40 m B=5 T, provide spin rotation by $\varphi = 180^0$
at E=45.5 GeV. Extension to 120 GeV with B=10 T looks feasible.
All quads don't need to be skewed! Spin transparency require:
Full Snake: $\cos\varphi = -1$, $\sin\varphi = 0$; 90^0 - spin rotator: $\cos\varphi = 0$, $\sin\varphi = 1$

Radiative polarization with Siberian snakes

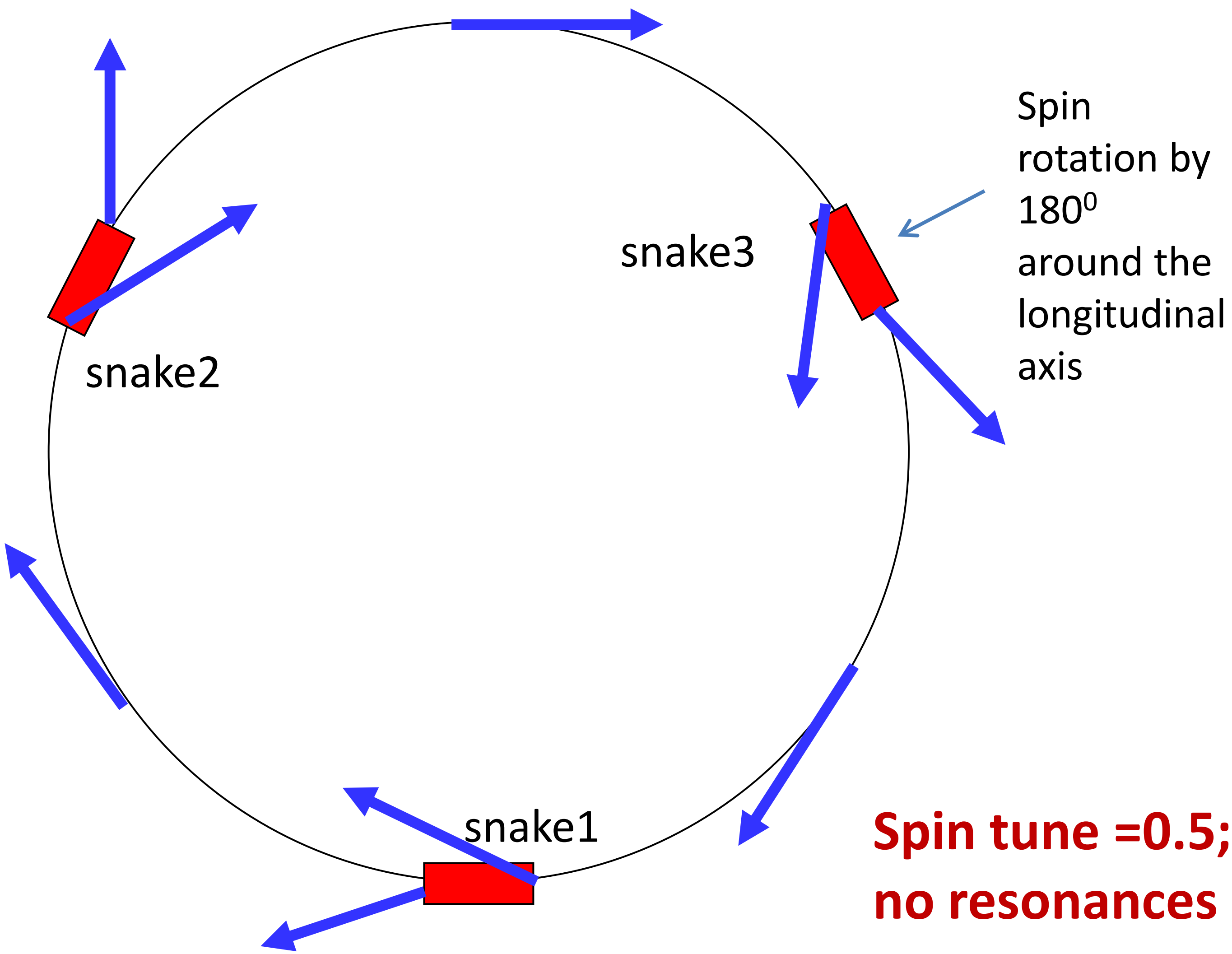








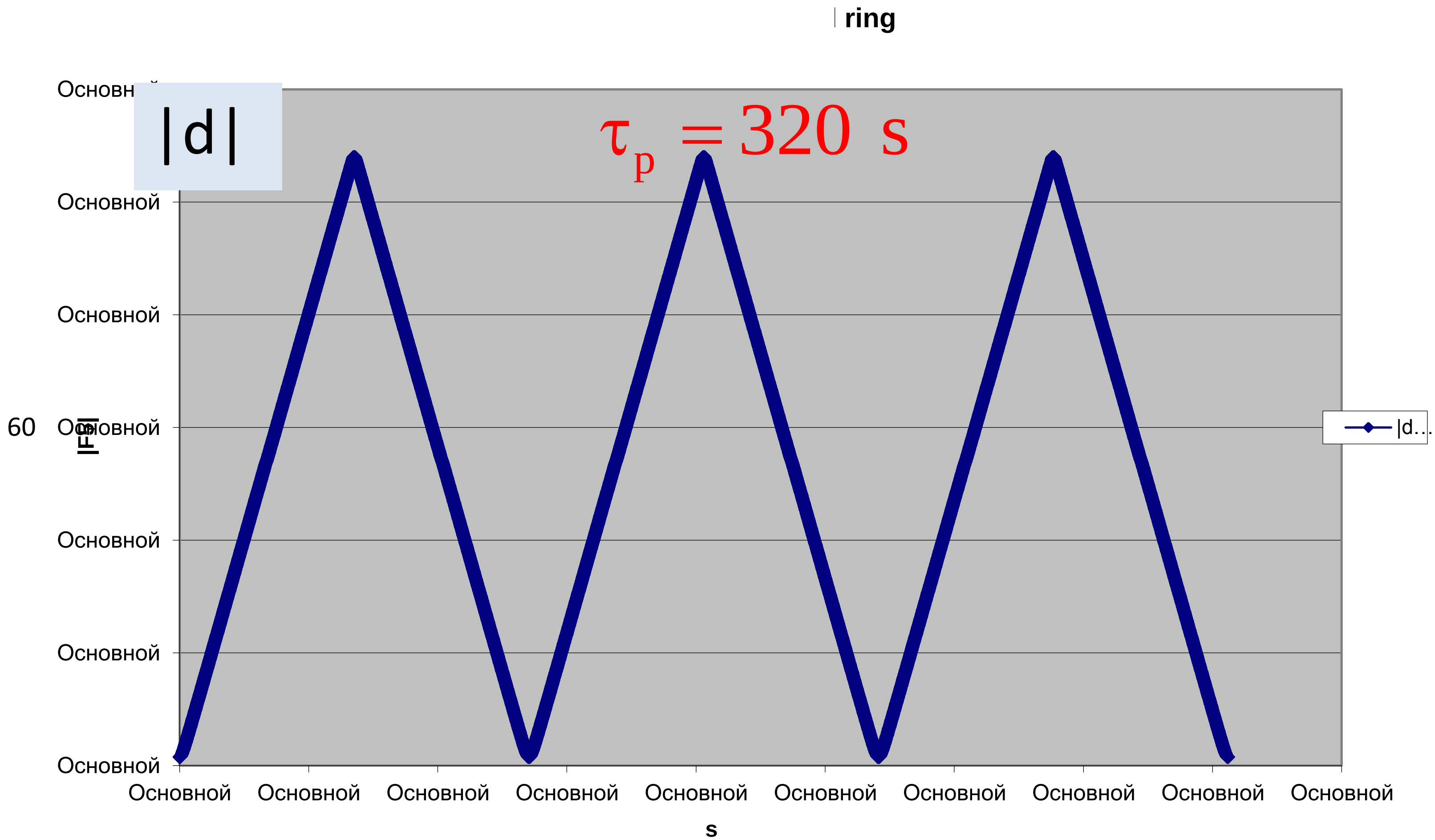
Ring with 3 Siberian snakes



Spin tune =0.5; no resonances

Spin response function $|F_5|=|d|$

Ring toy-model with 3 full snakes, E=45.5 GeV



Dynamic depolarization during acceleration with Siberian snakes

Dynamic depolarization during acceleration develops due to presence of spin resonances produced by the orbit distortions and the betatron oscillations (intrinsic).
Spin tracking simulation (S.Mane) with random errors in quads positions (0.1 mm) led to orbit deviation (maximum 1mm) in vertical and horizontal directions.
The horizontal and the vertical emittances were taken 3 pm and 30 fm, respectively. The modeled ring contains 3 snakes.
The polarization loss does not exceed $2\cdot10^{-4}$ for acceleration from 10 to 86 GeV in 55 s.

So, this effect is negligible, because all these resonances are very far from the half-integer spin tune value.

Acceleration with 3 snakes.

Energy scaling of the depolarization time:

With $\rho = \text{const}$, $\tau_p \propto \gamma^{-5}$ and $\tau_p \propto N^2$

With 3 snakes: $\tau_{45.5\ \text{GeV}} = 320\ \text{s}$

$\tau_{80\ \text{GeV}} = \tau_{45.5\ \text{GeV}} \cdot 0.019 = 6.2\ \text{s}$ - 10 s ramping time is OK?

With 9 snakes: $\tau_{80\ \text{GeV}} = 55.5\ \text{s}$ - 60 s ramp time fits well!

Synchrotron with two snakes looks better choice!.

Longitudinal polarization at Z peak

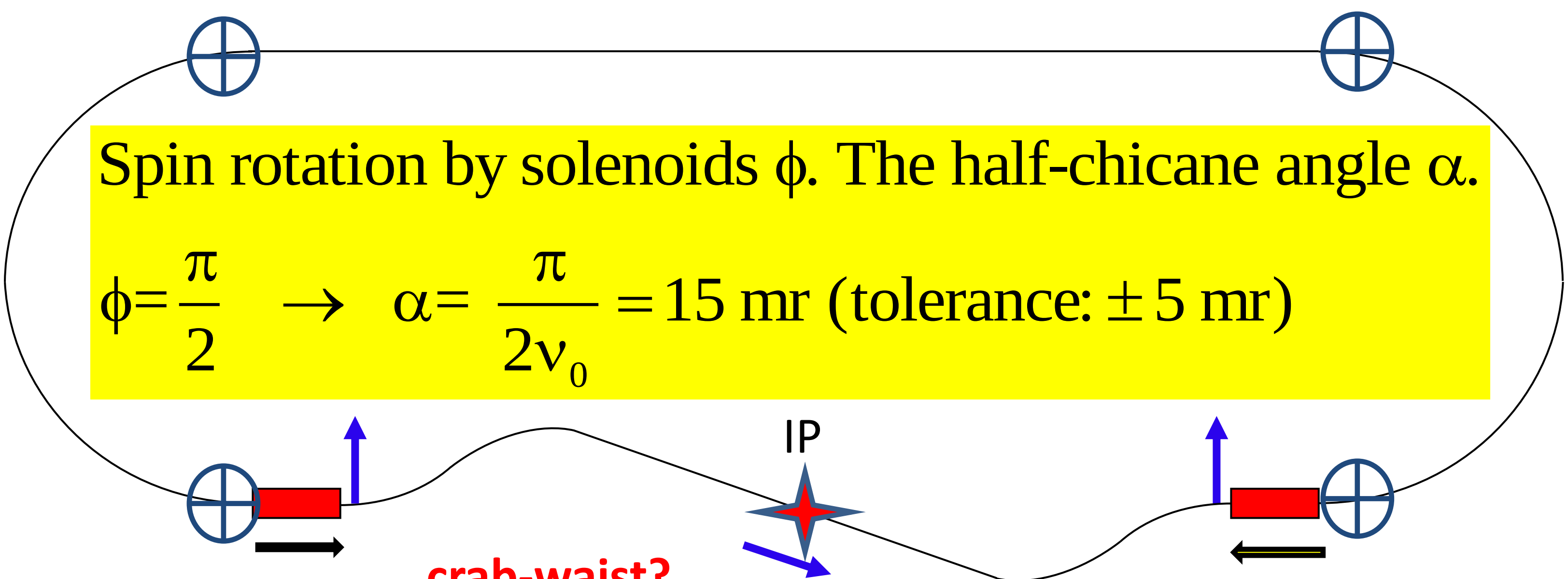
Two options for collider

1)Three snakes – polarization is longitudinal in opposite straight to one snake. $\tau_d \approx 300$ sec. Synchrotron ramping time 10 sec. Luminosity is $\ll L_{max}$; special runs for energy calibration.

2)Anti-symmetric spin rotator (chicane) in the Interaction region provides the longest depolarization time!

Spin rotation by solenoids ϕ. The half-chicane angle α.

$$\phi = \frac{\pi}{2} \quad \rightarrow \quad \alpha = \frac{\pi}{2\nu_0} = 15 \text{ mr (tolerance: } \pm 5 \text{ mr)}$$



Longitudinal polarization at Z peak

Advantage:
Solenoids are spin transparent.
Spin direction in arcs is vertical and achromatic: $|d|_{arcs}=0$.
Only chicane magnets contributed to the radiative depolarization,
Therefore the spin relaxation time exceeds 24 hours!
Crossing angle is compatible with the crab waist requirements.

L_{max} is available with high polarization.
Energy calibration with pilot non colliding bunches.

Precise energy calibration

Spin tune spread: A.P.Lysenko et al., Part.Accelerators, (1986) V.18, p.435.

$$\sigma_\nu = \frac{1}{\alpha}A_x^2\left\langle (K^3 - 2Kg_x - \frac{1}{2}n_1)|f_x|^2\psi_x + \frac{1}{2}(1+K\psi_x)\left(|f_x|'^2 + \frac{1}{|f_x|^2}\right) + K'\psi_x|f_x||f_x|'\right\rangle_\theta$$
$$+ \frac{1}{2}\left(\frac{\Delta\gamma}{\gamma}\right)^2\left\langle (K^3 - 2Kg_x - \frac{1}{2}n_1)\psi_x^3 + \frac{1}{2}(1+K\psi_x)\psi_x'^2 + \psi_x^2(K'\psi_x' + 2K - n)\right\rangle_\theta .$$

σ_ν can be controlled by secstupoles. $\frac{\Delta\gamma}{\gamma}$ =0.07% (E=45 GeV)

Let's assume $\sigma_\nu \approx 10^{-5}$.

Resonant depolarization with accuracy~10^{-6} available.

But, it's possible other more attractive option.

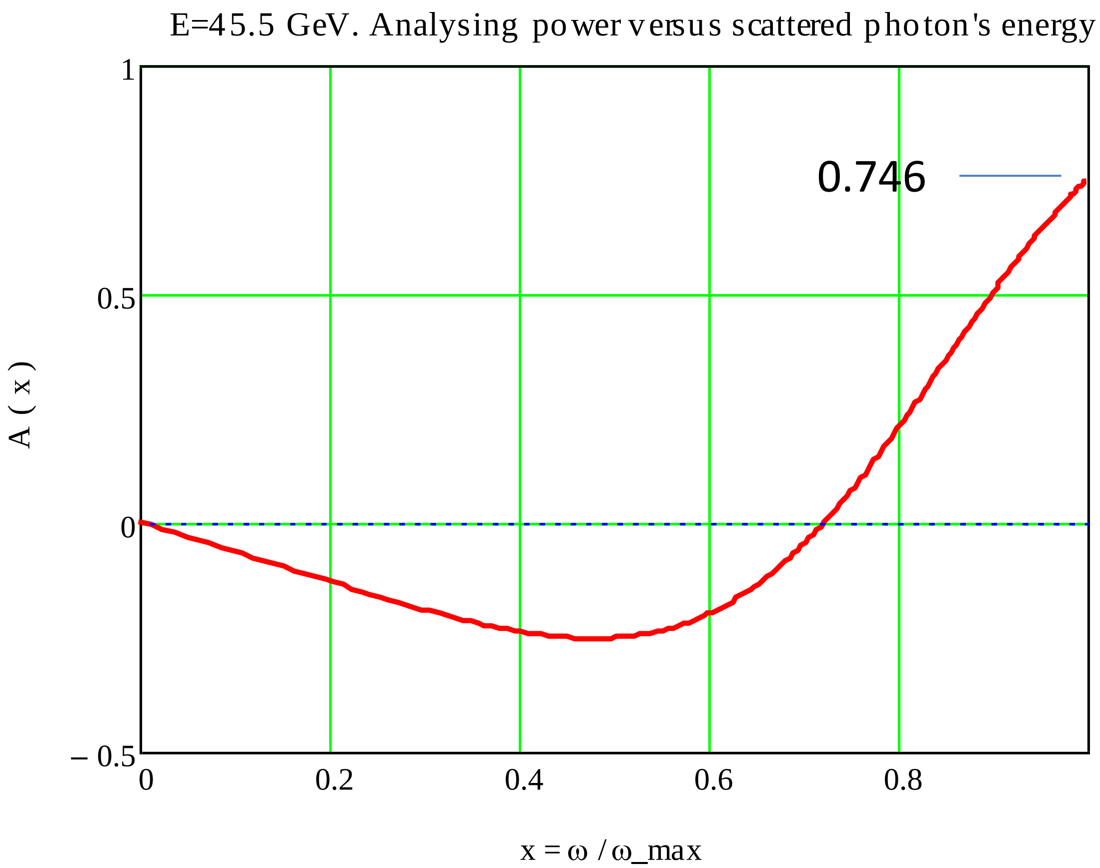
Spin half flip by rf (AC) dipole with Bx field (w_k~Bx F_3) or longitudinal polarized pilots bunches injection.

Then free spin rotations observation by Compton scattering.

Time of free precession T is determined by spin diffussion:

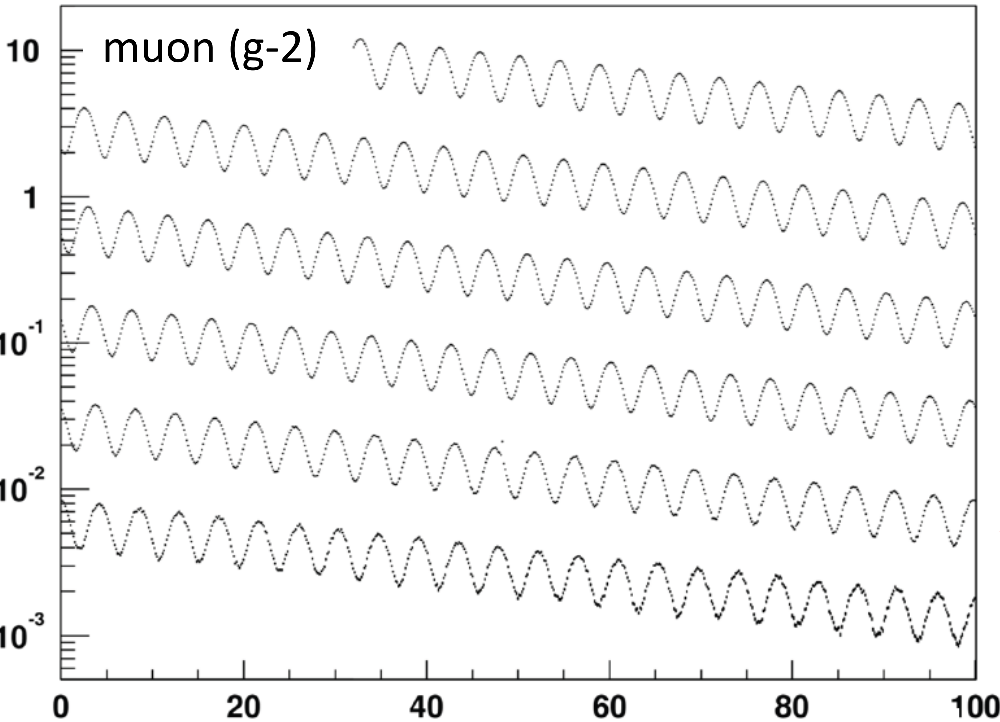
$\overline{(\delta\phi)^2} = \sigma_\nu^2 \cdot T\,\tau_0.$ ($T \gg \tau_0$ = 1300 turns.)

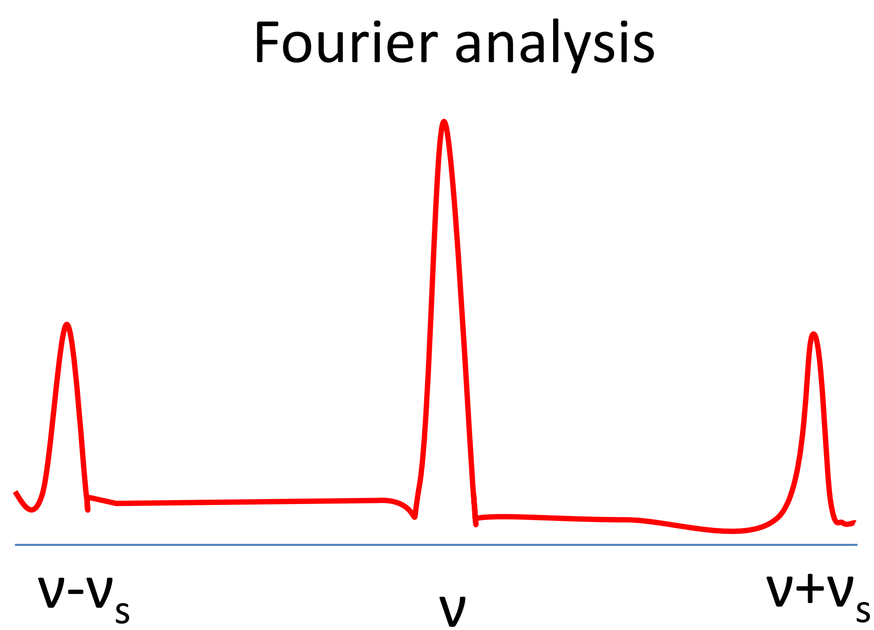
Compton scattering of a laser photons



The longitudinal Compton polarimeter should be used due to its huge sensitivity to the longitudinal component of the polarization. Detection of the scattered electrons provides excellent spectral selectivity to their energy loss. Thus, one can use events near the spectrum edge!

Free spin precession observation and analysis





Could be observed also other peaks, for example, from coherent betatron oscillations. But the central line will dominate always .

Systematics in the energy measurements

Resonance frequency: $\nu_R = k \pm \nu_s \pm m\nu_x \pm n\nu_y$

Detuning: $\varepsilon = \nu_0 - \nu_R$ with $\nu_0 = \gamma a$

Spin tune shift due to the nearest resonances

$$\delta\nu \sim \frac{1}{2}\sum_k \frac{|w_k|^2}{\nu_0 - \nu_k}$$

Tune scan and measurements are needed to clarify the systematics.

HSM should be applied to minimize the nearby resonances strength!

Conclusion

- Radiative polarization at flat machine is limited by an energy around 100 GeV.
- HSM can be improved with taking into account the spin response functions and high ν_γ.
- Siberian snakes suppress the synchrotron satellites.
- Acceleration of polarized electrons in a synchrotron equipped by two snakes is open up to 175 GeV .
- Longitudinal polarization at Z-peak can be done with solenoid type spin rotator at full stream in luminosity.
- Precise energy calibration up to W threshold is open.
- Free spin precession method based on the Compton polarimeter with analyzing power about 100% shall provide the energy determination in one shoot!

Thanks for attention!