Possible beam studies at VEPP-4M

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on behalf of VEPP-4M-KEDR team

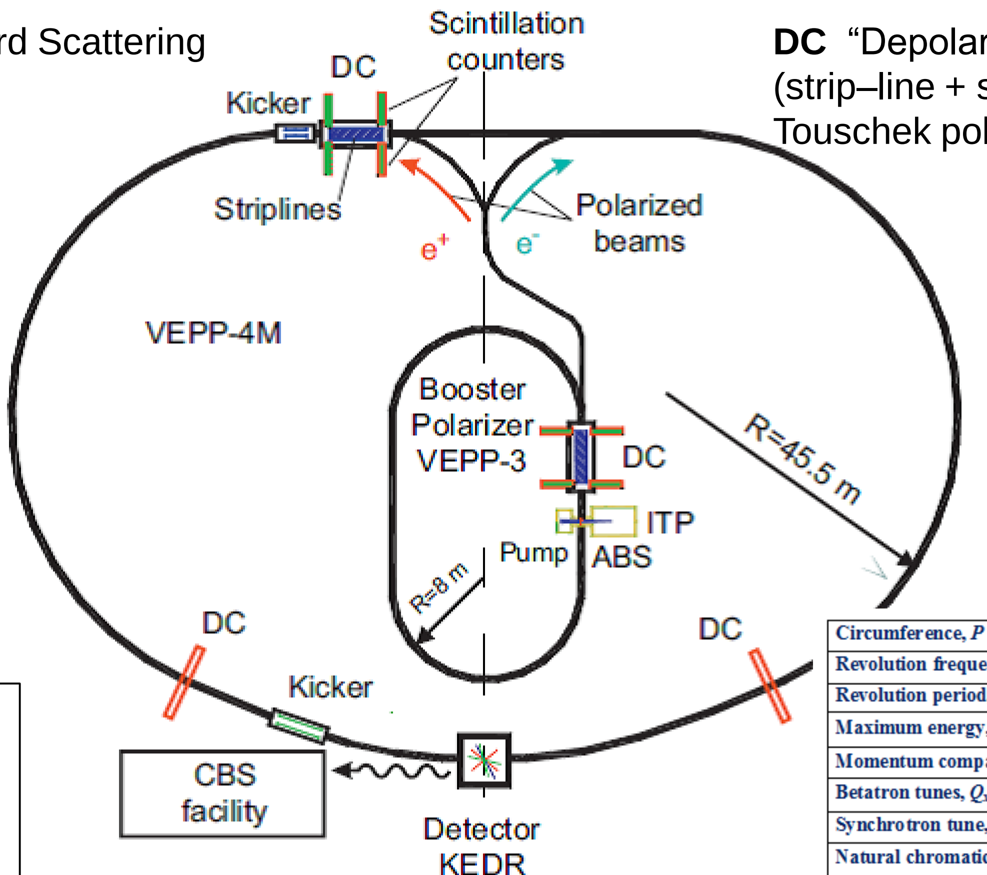
EU Horizon 2020 ''Future Circular Collider Innovation Study"

10 November 2020

VEPP-4M facility

CBS Compton Backward Scattering beam energy monitor/ laser polarimeter

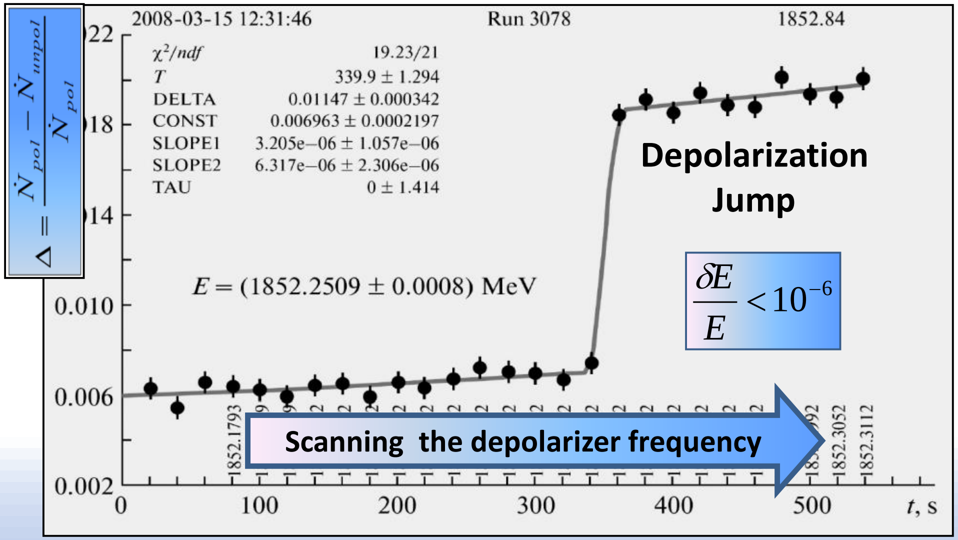
DC "Depolarizer-Counters" system (strip–line + scintillation counters of Touschek polarimeter)

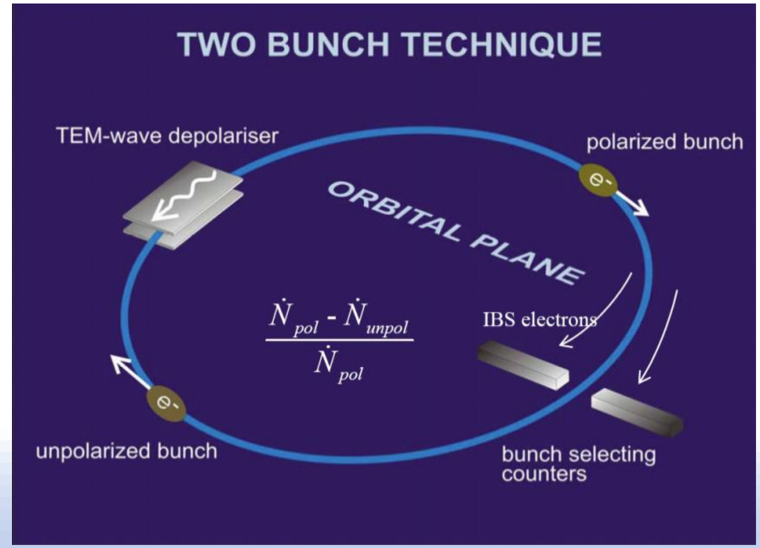


Mono-ring collider with $2e^+ \times 2e^-$ bunches and electrostatic orbit separation in 3 parasitic IPs

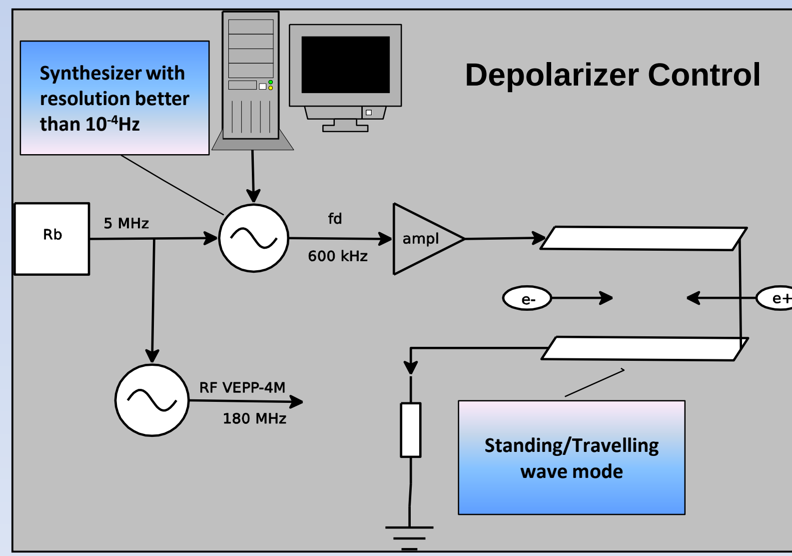
Circumference, P (m)	366.075
Revolution frequency, f_0 (kHz)	818.924
Revolution period, T_0 (ns)	1221
Maximum energy, E (GeV)	5.3*)
Momentum compaction factor, α	0.017
Betatron tunes, Q_x/Q_z	8.54/7.58
Synchrotron tune, Q_s	0.012
Natural chromaticity, ξ_x/ξ_z	–14.5/–20.3
Parameters at 1.8 GeV	
Damping times, $\tau_x/\tau_z/\tau_s$ (ms)	70/35/70
Horizontal emittance, ε_x (nm-rad)	17
Energy spread, σ_E/E	4×10^{-4}
Bunch length, σ_L (cm)	6
Energy loss/turn, ΔU (keV)	16
IP optical functions, β_y / β_x / η_x (m)	0.05/0.7/0.78

Energy calibration using Touschek polarimeter





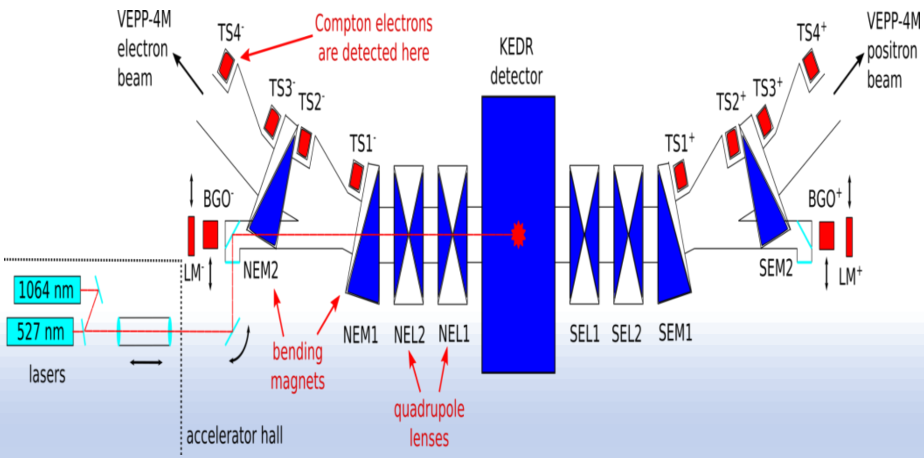
- Depolarization jump $\Delta\left(\frac{\dot N_{pol}-\dot N_{unpol}}{\dot N_{pol}}\right)\propto \zeta^2$
- Scattered (Touschek) electron count rate ~ **1 MHz/mA**
- Touschek particle fraction in total rate **~ 60-80%** (E < 2 GeV)
- Common Rb standard (**10^{-10}**) of frequency for VEPP-4M RF system master clock and for depolarizer synthesizer to exclude effect of their drifts
- Revolution frequency stability **$\Delta\omega_0/\omega_0 \sim 10^{-10}$** → beam energy stability **$\Delta E/E \sim \alpha^{-1}\Delta\omega_0/\omega_0 \sim 6\cdot10^{-9}$** , momentum compaction factor **α=0.017**
- Limitation in accuracy of absolute energy calibration: own width of spin frequency line due to quadratic nonlinearity of guide field $\frac{\delta E}{E}=\frac{\delta\nu}{\nu}\sim\langle H''\cdot(\sigma_{x\beta}^2+\sigma_{xs}^2)\rangle\sim 5\cdot10^{-7}$
- Accuracy: **δE=2 keV (10^{-6})**



VEPP-4M CBS facility

Laser polarimeter

V.E.Blinov at al., 2020 JINST 15 C08024
https://iopscience.iop.org/article/10.1088/1748-0221/15/08/C08024/meta



- Pulsed DPSS Nd:YLF laser with 2nd harmonic generation (http://laser-export.com/prod/527.html):
  - 527 nm;
  - 7 ns pulse duration
  - 100 … 150 μJ in pulse;
  - 1 … 2 kHz repetition rate.

Compton Back Scattering beam energy monitor

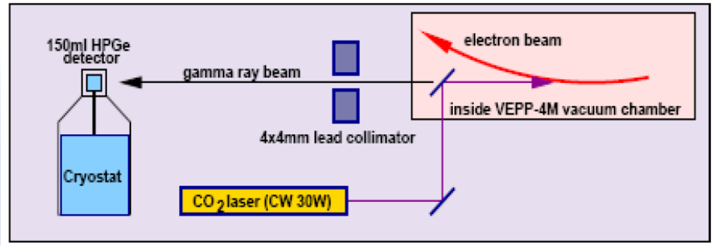
N.Yu. Muchnoi, *Conf.Proc.C* 060626 (2006) 1181-1183,
https://inspirehep.net/literature/737911

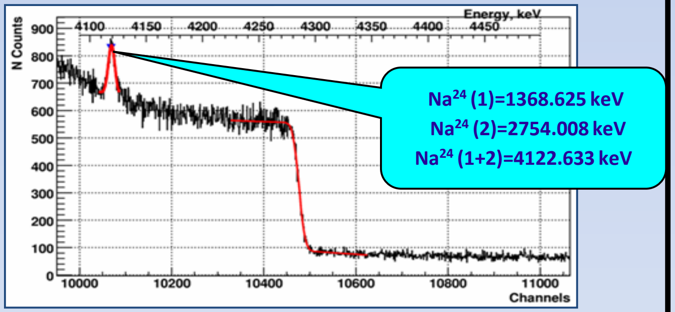
- R. Klein et al., NIM A384 (1997) 293: BESSY–I, 800 MeV
- R. Klein et al., NIM A486 (2002) 545: BESSY–II, 1700 MeV

$$\omega_{max} = \frac{E^2}{(E + m_e^2/4\omega_0)} \simeq 4\gamma^2\omega_0$$

$$E = \frac{\omega_{max}}{2}\left(1 + \sqrt{1 + \frac{m^2}{\omega_0\omega_{max}}}\right)$$

VEPP-4M, 2006-11, 900-2000 MeV





- Accuracy ~ 5×10^{-5} , t_{meas} ~ 10 min
- Beam energy spread measurement (7-10%)
- Energy monitoring during statistics acquisition
- Limitation in beam energy E_b <3.5 ГэВ (ω_{max}<6 MeV)

Effects and instrumental possibilities of interest to study

1. **Resonant spin diffusion** due to large spin tune spread. Presumably, this can be relevant for FCCee at 45 GeV (wiggler mode) and at 80 GeV (no wigglers) . This effect was not so relevant in e+e- storage rings of several GeV. It remains as yet unexplored

2. **"Fan" (free precession) Polarization.** Its implementation would make it possible to measure energy by spin precession frequency immediately after injection of beam with polarization directed across field. Discussion on results of the **"Pulsar"** experiment performed at VEPP-4M

3. **Crossing spin resonances** under ramping energy. This can be useful in the viewpoint of possibility to accelerate polarized beams in a booster of future lepton colliders. For this purpose, Partial Siberian Snake must be inserted into a booster. Results and prospects of similar experiments at VEPP-M

4. **Features of Resonant Depolarization application** in various conditions

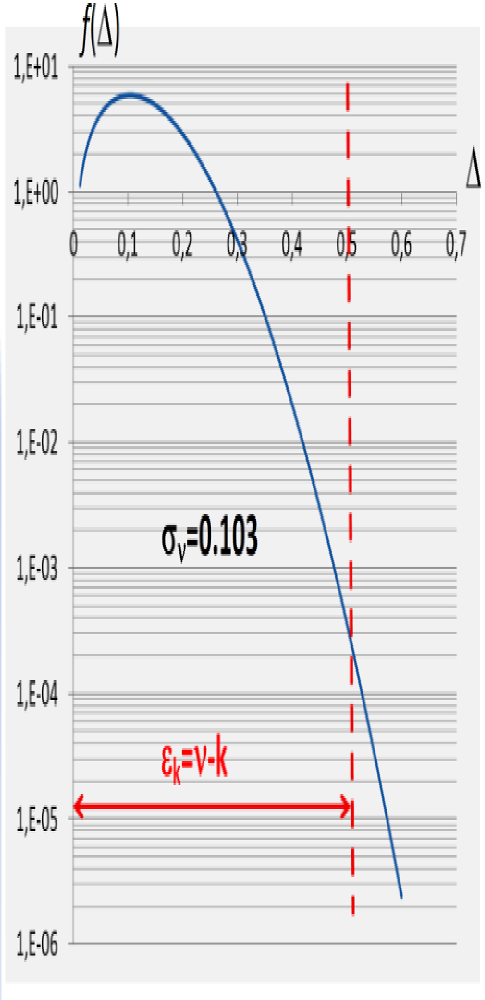
Resonant diffusion of polarization in future lepton colliders

S. Nikitin, Talk at CEPC Workshop, IHEP, Beijing 12-14 Nov. 2018 ;
International Journal of Modern Physics A, Vol. 35 (2020) 2041001

It was not relevant in electron-positron rings at low and middle energies.

Resonant diffusion due to large instant spin tune spread (at 45 GeV, $\sigma_\nu \approx 0.1$ in wiggler mode) should be considered in framework of model basing on radiative excitation and damping. For particle falling into tail of distribution function, amplitude of spin tune modulation by synchrotron oscillations can sporadically overlap distance to closest spin integer resonances ($\varepsilon_k \approx 0.5$). As result, there are accidentally recurring fast intersections of those resonances…

Modulation amplitude distribution



Suggested model

$\nu = \bar{\nu} + \Delta \cdot \cos \Psi_\gamma$ synchrotron modulation of spin tune

$\Psi_\gamma' = d\Psi_\gamma / d\theta = \nu_\gamma$ synchrotron tune

$f(\Delta) = \Delta \cdot \exp(-\Delta^2 / 2\sigma_\nu^2) / \sigma_\nu^2$ distribution function density

$\sigma_\nu^2 = \nu^2 \sigma_E^2 / E^2$ dispersion of spin tune due to energy spread

$\varepsilon_k = \nu - k$ detuning from resonance with number k

$|w_k|$ spin harmonic amplitude

$\langle \varepsilon' \rangle \sim \sigma_\nu \Lambda_\gamma$ average rate-of-change of detuning due to diffusion

Λ_γ radiation decrement of synchrotron oscillations

f_0 revolution frequency

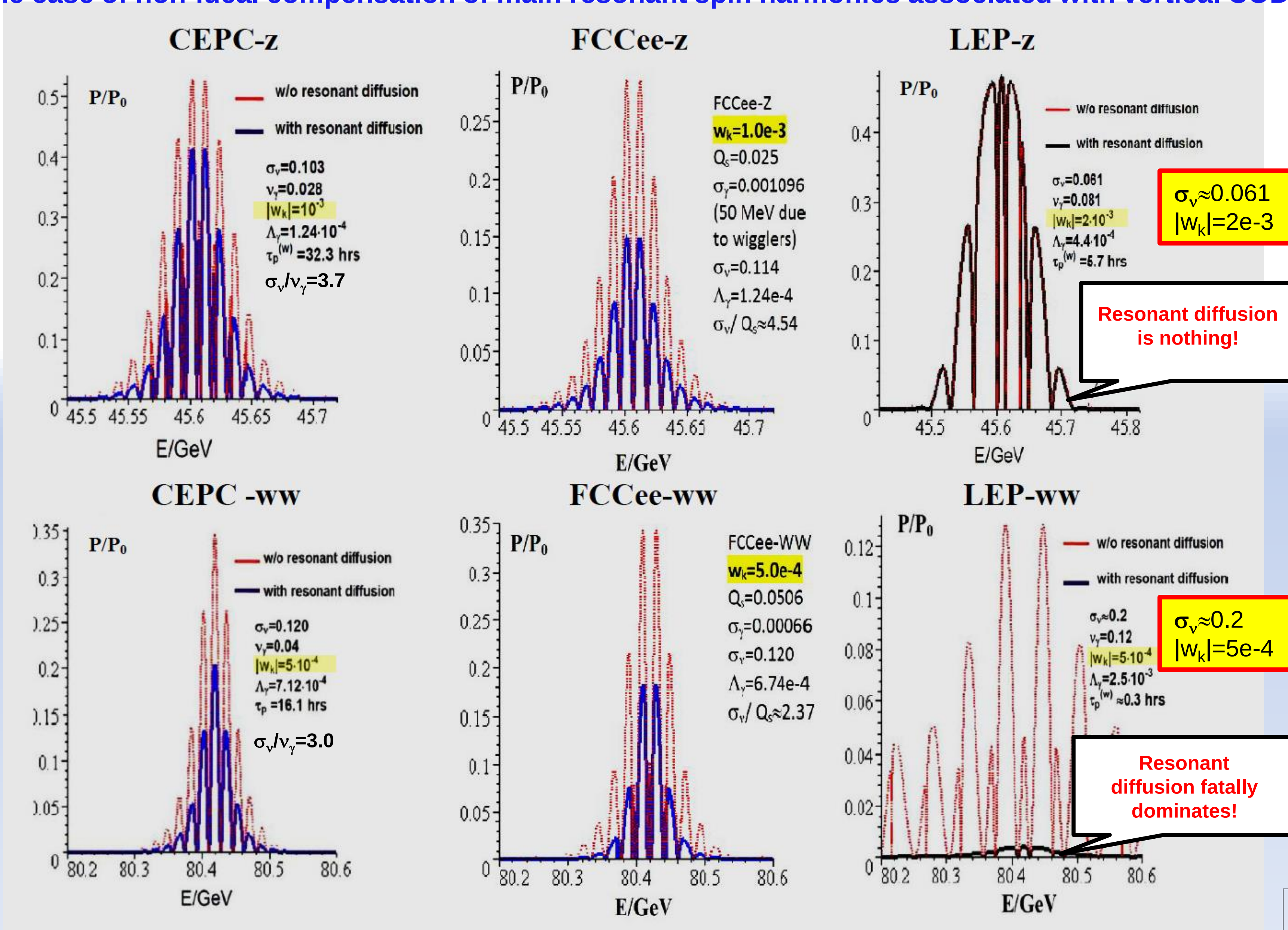
Resonant diffusion rate in approximation of fast crossings due to joint effect of synchrotron oscillations and radiation processes:

$$\frac{1}{\tau_{res}} \approx 2\pi f_0 \frac{|w_k|^2}{\sigma_\nu^2} \int_{\varepsilon_k}^{\infty} \frac{\Delta \cdot e^{-\frac{\Delta^2}{2\sigma_\nu^2}}}{\sqrt{\Delta^2 - \varepsilon_k^2 + (\sigma_\nu \Lambda_\gamma / \nu_\gamma)^2}} d\Delta$$

How this can be dangerous?

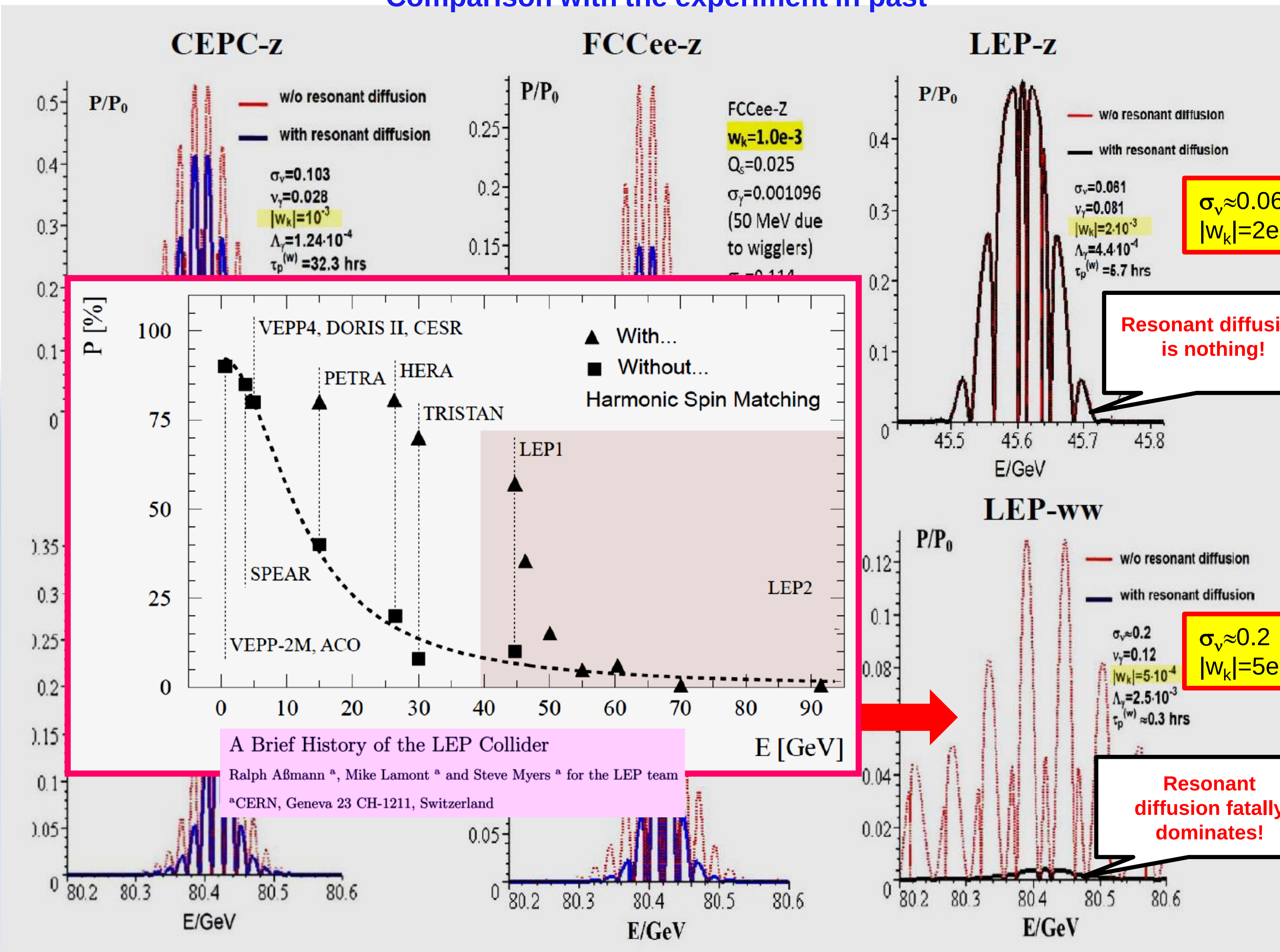
Combined effect of non-resonant and resonant diffusions

The case of non-ideal compensation of main resonant spin harmonics associated with vertical COD



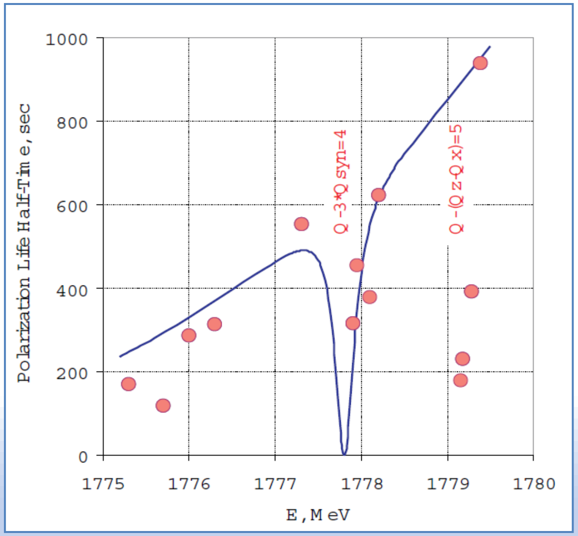
Combined effect of non-resonant and resonant diffusions

Comparison with the experiment in past

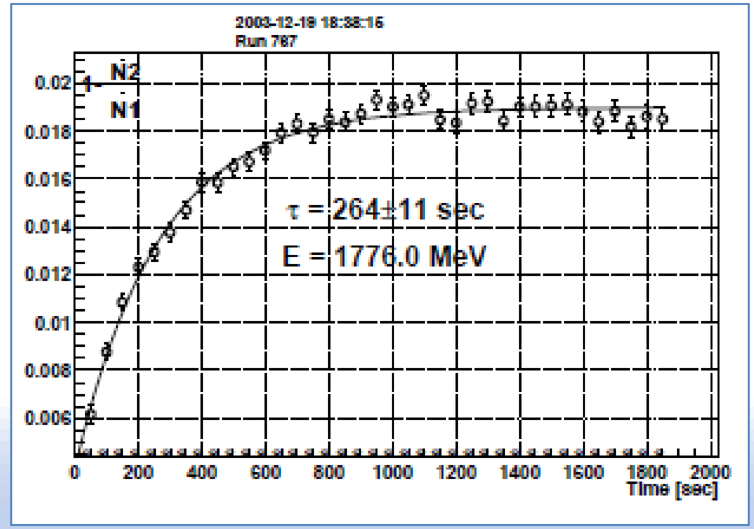


Polarization lifetime versus resonance detuning

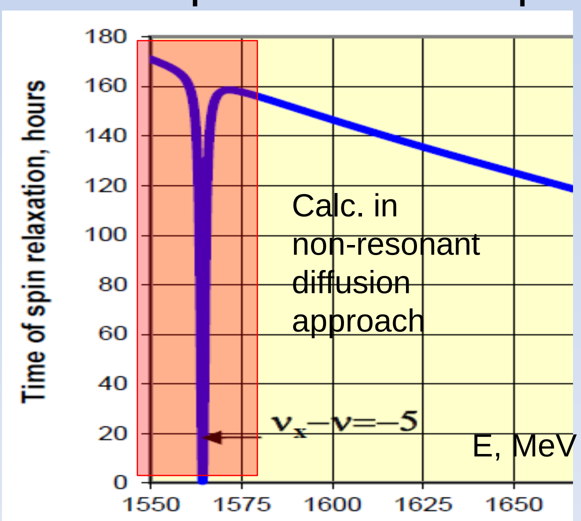
Measured fine structure of spin resonances near to integer one



Natural depolarization process observed with Touschek polarimeter near to integer resonance ν=4



Depolarization spin-beta resonance simulated at 100 um dispersion of offsets of quads

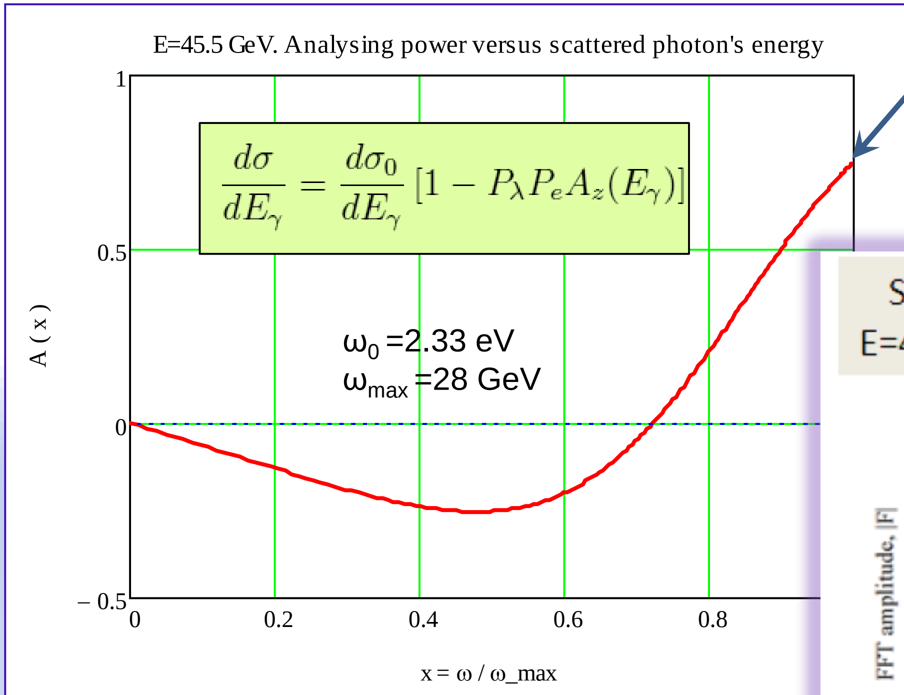


One example of what to try

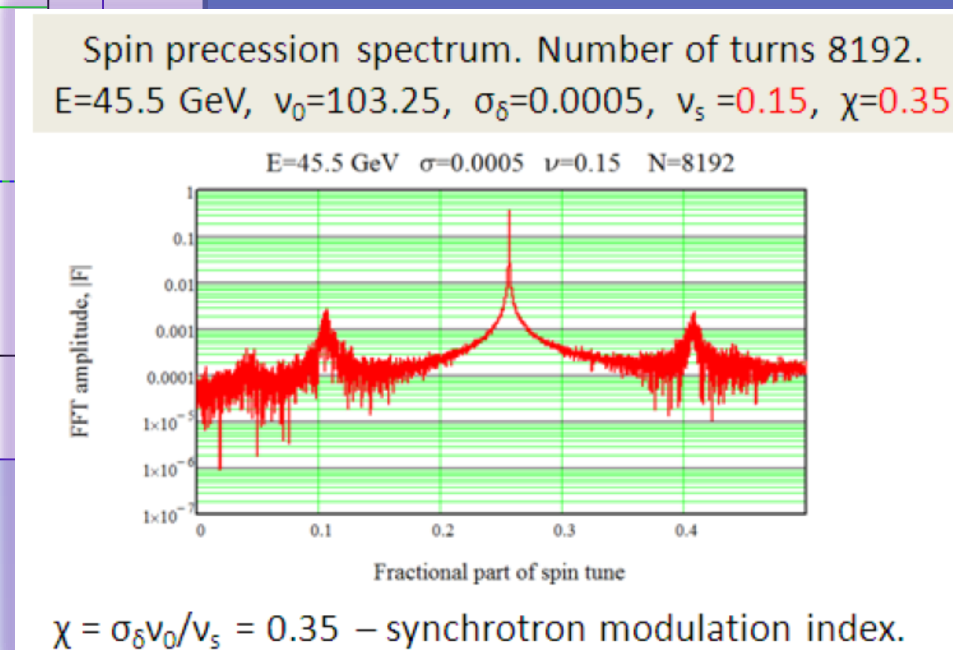
Region of possible **study of effect of resonant spin diffusion** via the dependence of polarization lifetime on resonance detuning ~ 10^{-3} at different spin tune spread.

Nominal spin tune spread ~ 10^{-3}
It can be varied via changing the damping partition number for energy oscillations (using the Robinson wigglers)

Concept by I.Koop for FCCee beam energy measurement at injection (HF2014)



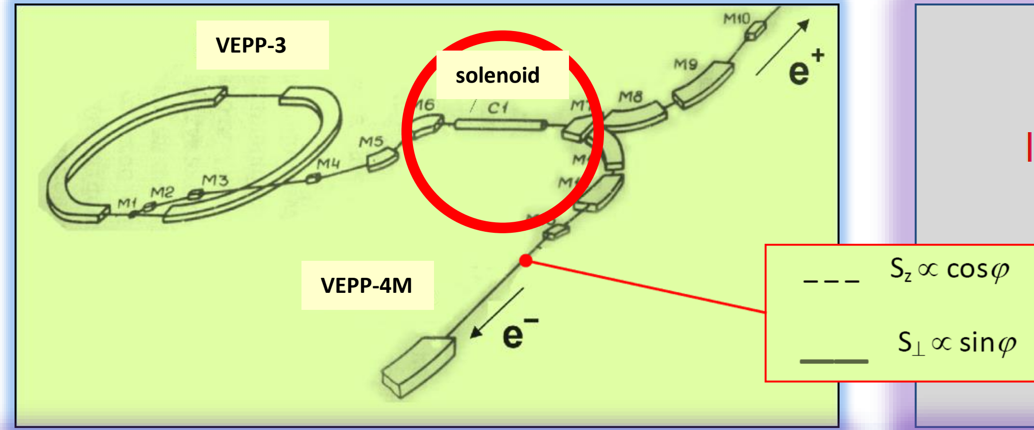
"Detection of the scattered electrons instead of photons provides selection of events with maximal momentum loss! Let's utilize the highest value of the analysing power! "

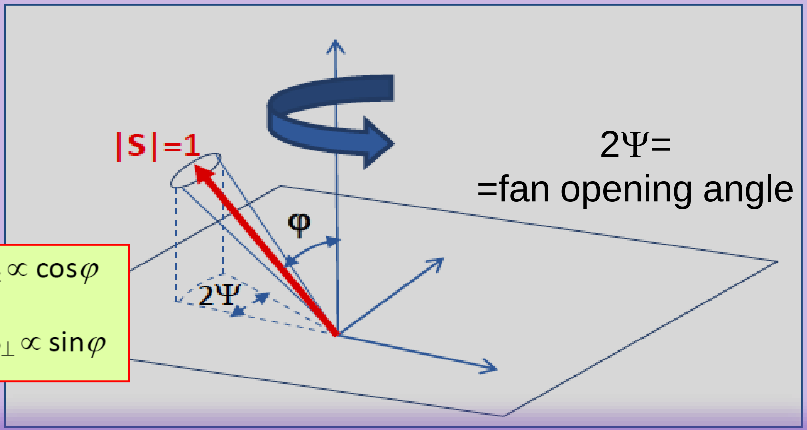


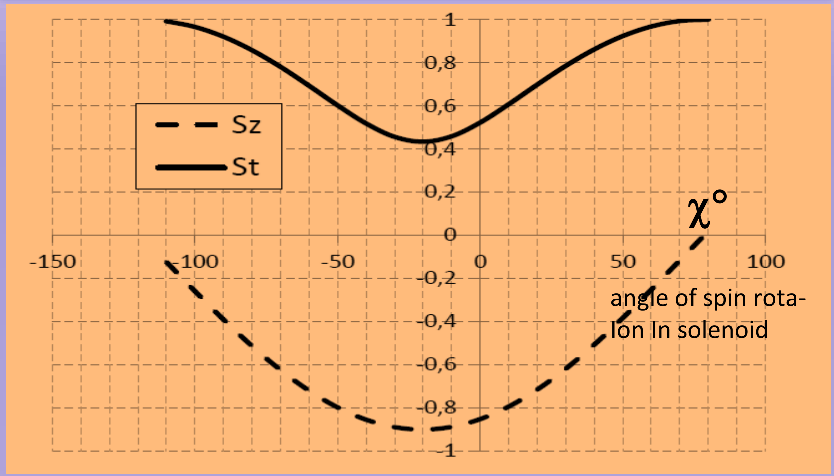
"Injection of polarized bunches into the collider rings with the horizontal spin orientation and measuring turn by turn the free precession frequency using longitudinal Compton polarimeter."

“Pulsar” Fan Polarization test (VEPP-4M, 2015)

V. Kaminskiy, V. A. Kiselev, E.B. Levichev, S.A. Nikitin, I.B. Nikolaev, A. N. Zhuravlev





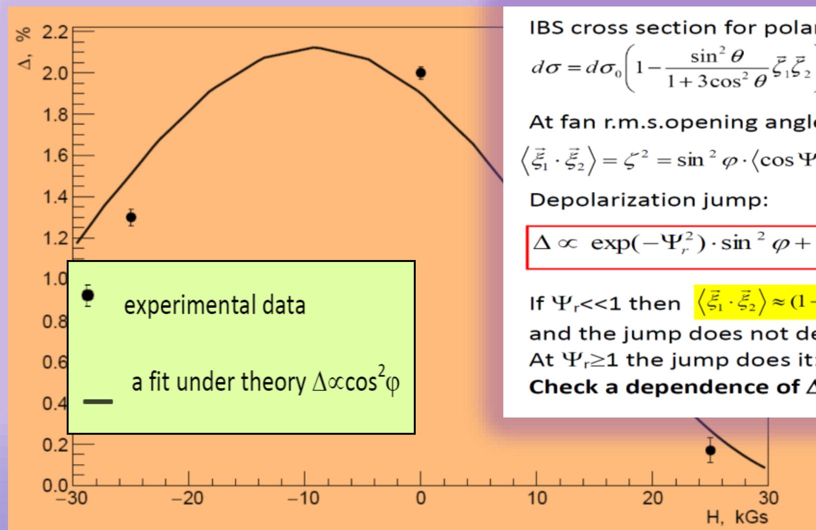


- Pulsed solenoid provides an angle φ of (0 – 90)° at injection of 1.5 GeV electron beam
- Measurement: CBS (during injection) + Touschek polarimeter (in stationary conditions after injection)
- Possible evidences of Fan Polarization:
  - modulation of the Compton intensity with the spin precession frequency
  - independence of the measurements by the Touschek polarimeter on the angle φ

VEPP-4M

Results of “Pulsar” experiment

Depolarization jump observed with Touschek polarimeter versus pulsed solenoid field



IBS cross section for polarized beam:

$$d\sigma = d\sigma_0\left(1-\frac{\sin^2\theta}{1+3\cos^2\theta}\vec{\zeta}_1\vec{\zeta}_2\right),\quad \vec{\zeta}_1\vec{\zeta}_2=\zeta^2$$

At fan r.m.s.opening angle Ψ_r:

$$\langle\vec{\xi}_1\cdot\vec{\xi}_2\rangle = \zeta^2 = \sin^2\varphi\cdot\langle\cos\Psi_r\rangle+\cos^2\varphi$$

Depolarization jump:

$$\Delta \propto \exp(-\Psi_r^2)\cdot\sin^2\varphi+\cos^2\varphi$$

If $\Psi_r<<1$ then $\langle\vec{\xi}_1\cdot\vec{\xi}_2\rangle \approx (1-\Psi_r^2)\cos^2\varphi+\sin^2\varphi\approx 1$

and the jump does not depend on φ!

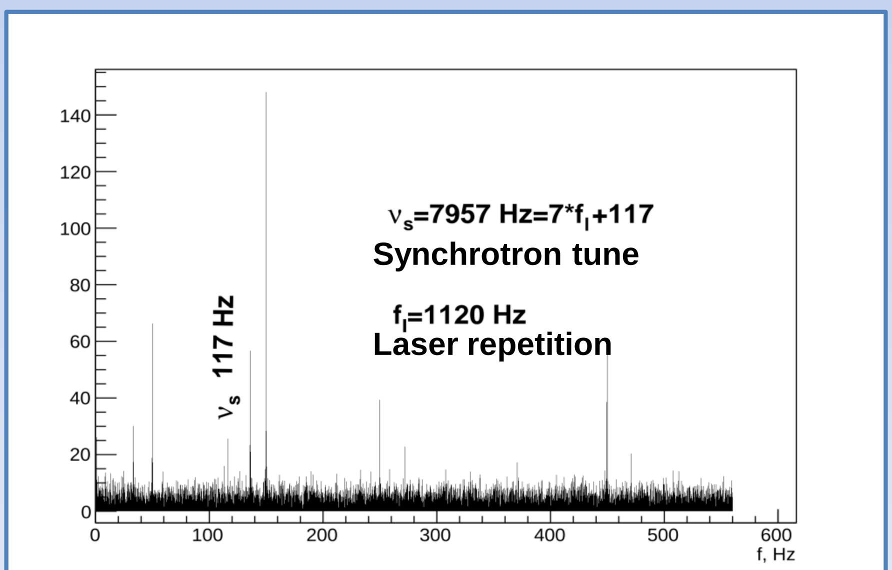
At $\Psi_r\geq 1$ the jump does it: $\Delta\propto\cos^2\varphi$

Check a dependence of Δ on the solenoid field!

Fan polarization was absent some time of the order of 10 minutes after injection (time needed to carry out the resonant depolarization procedure)

No long–term Fan polarization found!

Spectrum of Compton electron intensity



Compton electron counting rate 1-2 kHz
Measurement time **130 s**
Normalization by laser power
Discrete Fourier analysis:

- ✓ 50 Hz harmonics
- ✓ Betatron frequencies
- ✓ Synchrotron frequency

No spin precession frequency in spectrum was observed!

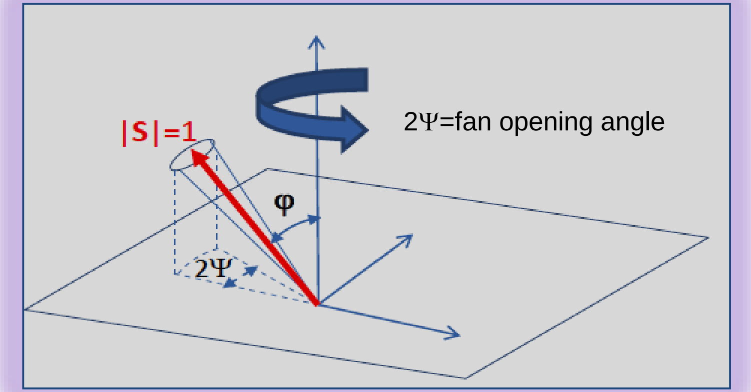
Fan Polarization formation starting from injection

Linear theory

Equilibrium r.m.s. angle formed in radiative damping time Λ^{-1}

$$\Psi_r^2 = \frac{2}{\Lambda}\frac{\nu^2}{\nu_\gamma^2} D_\gamma = \frac{\nu^2}{\nu_\gamma^2}\sigma_\gamma^2 . \quad 2\Psi_r \approx 12^\circ \quad (10^5 \text{ turns},\ \Lambda^{-1} \sim 0.1\,\text{s}, \sigma_\gamma \approx 3.5\cdot 10^{-4})$$

ν spin tune; ν_γ synchrotron tune; Λ radiation decrement;
σ_γ equilibrium energy spread, D_γ radiative diffusion rate



Stochastic model to account for quadratic nonlinearity of guiding field

Spin tune spread due to non-linearities

$$\delta\nu \approx \nu\sqrt{\left\langle H''\left(\overline{x_\beta^2 + x_\gamma^2}\right)\right\rangle^2 + \left(\frac{\alpha}{2}\sigma_\gamma^2\right)^2} \approx \nu\left\langle H''\left(\overline{x_\beta^2 + x_\gamma^2}\right)\right\rangle$$

$$x_\beta^2 = 4|a_x|^2 \beta_x \cos^2\psi_x, \quad x_\gamma^2 = 4|a_\gamma|\eta_x^2 \cos^2\psi_\gamma$$

Rate of precession angle change in respect to average

$$\mu_\beta \approx 2\nu\left\langle H''\beta_x\left(|a_x|^2 - \overline{|a_x|^2}\right)\right\rangle \quad \text{similar with } \mu_\gamma$$

Langevin's equation for stochastic behavior of μ_β

$$\frac{d\mu_\beta}{d\theta} + \Gamma\mu_\beta = F(\theta), \quad \overline{F(\theta)F(\theta')} = 2\Gamma^2 D\delta(\theta - \theta'), \quad \overline{F(\theta)} = 0$$

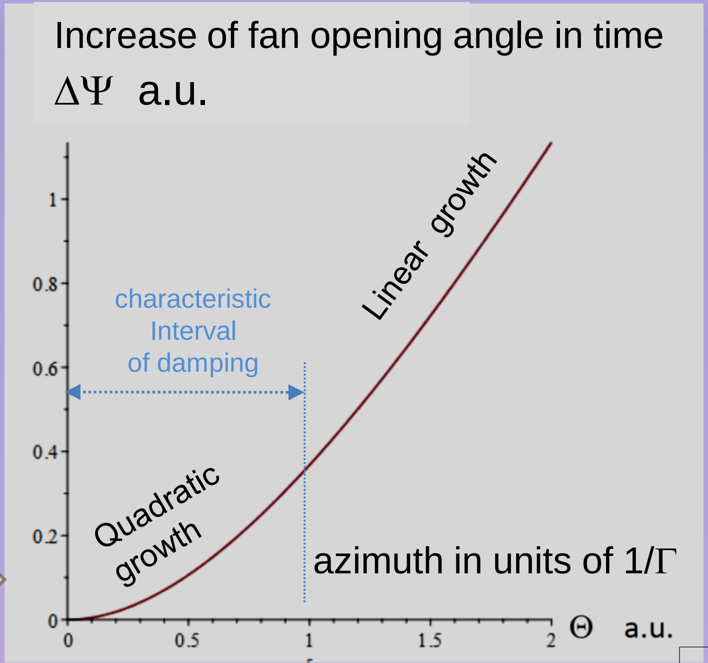
Fan angle spread due to non-linearity grows with time

$$\overline{(\Delta\Psi)_\beta}^2 = \overline{\left(\int_0^\Theta \mu_\beta(\theta)d\theta\right)^2} \approx \int_0^\Theta\int_0^\Theta \overline{\mu_\beta(\theta_1)\mu_\beta(\theta_2)}\,d\theta_1 d\theta_2,$$

$$\overline{\mu_\beta(\theta_1)\mu_\beta(\theta_2)} = D\Gamma\exp\left(-\Gamma|\theta_1 - \theta_2|\right), \quad \overline{\mu_\beta^2} = D\Gamma,$$

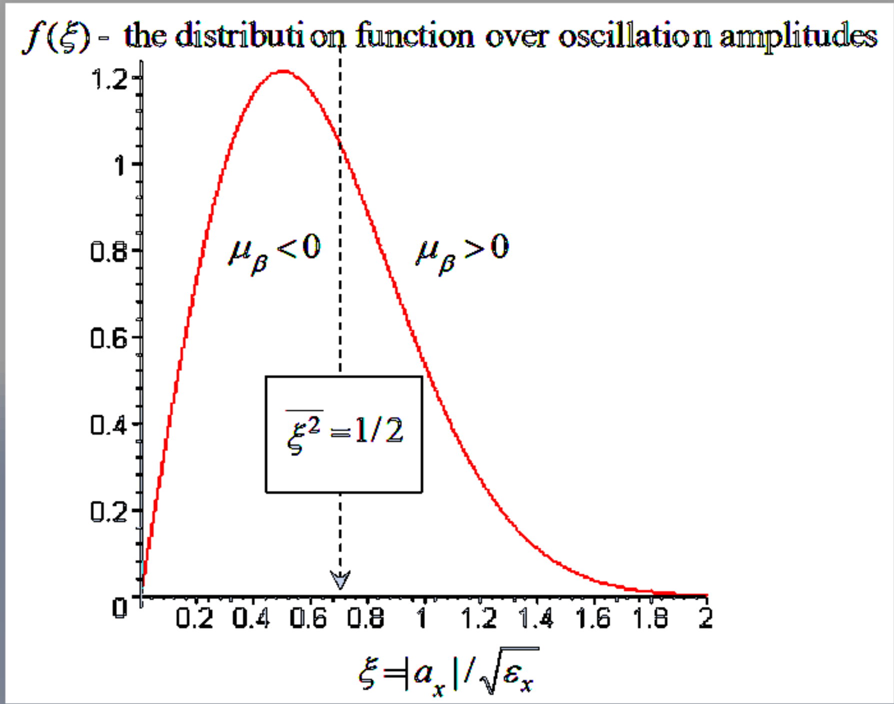
$$\overline{(\Delta\Psi)_\beta}^2 = D\Gamma\left(\frac{\Theta}{\Gamma} + \frac{e^{-\Gamma\Theta}}{\Gamma^2} - \frac{1}{\Gamma^2}\right) \approx \begin{cases} 2\overline{\mu_\beta^2}\Theta/\Gamma, & \Theta >> \Gamma^{-1} \\ 2\mu_\beta^2\Theta^2 e^{-1}, & \Theta \approx \Gamma^{-1} \end{cases}$$

$D,\ \Gamma = 2\Lambda_x$ the radiative diffusion rate and decrement



Estimate of fan opening angle growth due to factor *H”*

“Bunch of drunken sailors in strong crosswind”



$x_\beta = a_x f_x e^{i\nu\theta} + c.c.$

$\mu_\beta \approx 2\nu\langle H''\beta_x(|a_x|^2 - \overline{|a_x|^2})\rangle$

Betatron contribution to the rate of nonlinearity-related increment of precession phase with respect to the ensemble mean (“crosswind”)

$\overline{\mu_\beta^2} \approx \nu^2\langle H''\beta_x\rangle^2 \frac{\varepsilon_x^2}{2}$; $\varepsilon_x^2 = 2\overline{|a_x|^2}$; $\langle\ldots\rangle / \overline{\ldots}$ azimuthal /ensemble averaging

$\overline{(\Delta\Psi)_\beta^2} \approx \nu^2\langle H''\beta_x\rangle^2 \frac{\varepsilon_x^2}{4e}\Lambda_x^{-2}$, for damping interval $\Lambda_x^{-1} = 2\Gamma_x^{-1}$

$E = 1.5$ GeV; spin freq. linewidth $\frac{\delta\nu}{\nu} \sim 10^{-6}$

$\langle H''\rangle \approx \frac{\delta\nu}{\nu} / \langle\overline{x_\beta^2} + \overline{x_\gamma^2}\rangle \approx 5\cdot 10^{-4}$ cm^{-2}; $\varepsilon_x \approx 2\cdot 10^{-6}$ cm·rad

$\Theta = \Lambda_x^{-1} = 2\pi f_0 \tau_x$; $\tau_x \approx 0.2$ s

$\sqrt{\overline{(\Delta\Psi)_\beta^2}} \approx 0.8$ rad; $\Delta\Psi \approx \sqrt{\overline{(\Delta\Psi)_\beta^2} + \overline{(\Delta\Psi)_\gamma^2}} \approx \sqrt{2\overline{(\Delta\Psi)_\beta^2}} \approx$ **1.2 rad**

“Pulsar”: the fan broadening on the damping time scale significantly (injected beam emittance is several times more than its equilibrium value) exceeded 1 radian.
If we repeat experiment, then in more severe conditions:

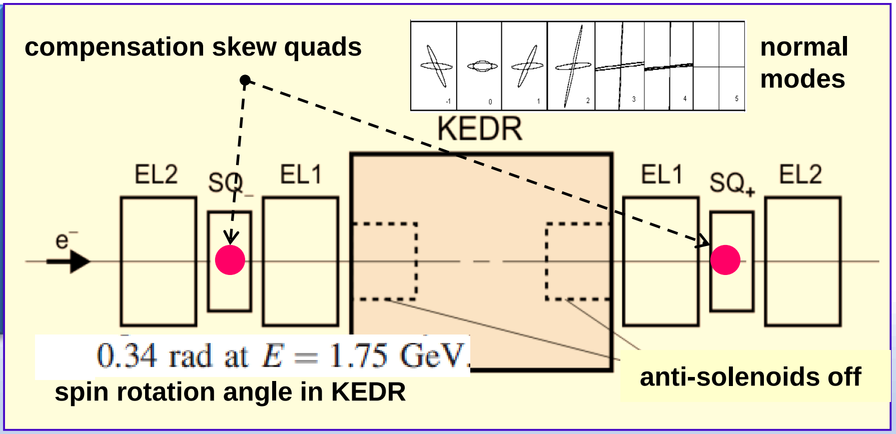
- **Organize the sextupole families to reduce the factor <*H”*> tenfold and more**
- **Reduce the measurement time with the laser polarimeter as far as the sensitivity allows in order to increase the proportion of useful events**

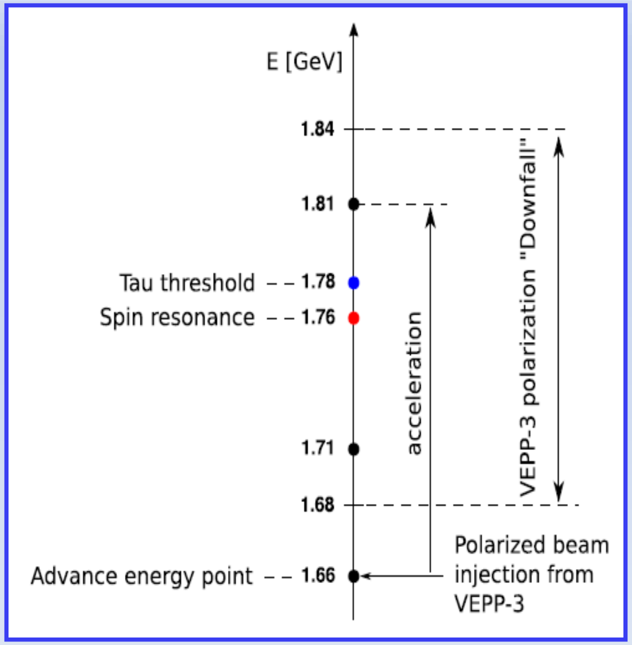
Crossing integer spin resonance using Partial Siberian snake (2016)

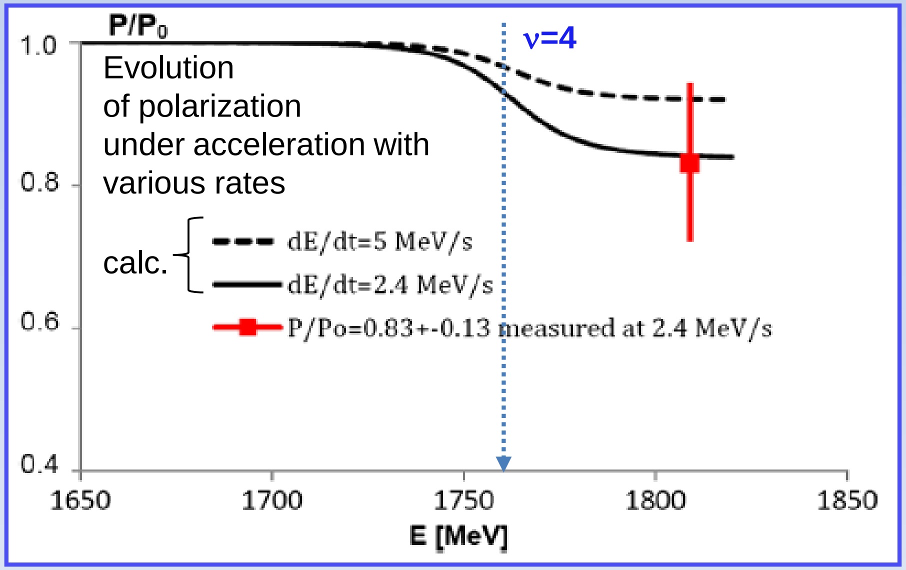
A.K. Barladyan, A.Yu. Barnyakov, S.A. Glukhov, S.E. Karnaev, E.B. Levichev, S.A. Nikitin, I.B. Nikolaev, I.N. Okunev, P.A.Piminov, A.G. Shamov, A.N. Zhuravlev, *DOI:10.1103/PRAB 22.112604*

Switch off anti-solenoids, use 0.6 T·m KEDR longitudinal field as Partial Siberian Snake (PSS) and adiabatically cross the integer resonance at 1763 MeV

World Background:
- Partial Siberian Snake technique was first tested with protons at IUCF and is currently used in BNL
- VEPP-2M's experiment in the end of 80s







Why study crossing spin resonances?

- Alternative way to obtain polarization in future lepton colliders - via acceleration of polarized beams in booster

- Unique way leading to possibility of obtaining longitudinal polarization at 45 GeV

- Unlike proton machines, this technique in e+e- rings has been much lesser studied (specificity is complication associated with depolarization due to synchrotron radiation)

- Use of PSS in booster (up to 45 GeV) to avoid main spin integer and spin-beta resonances
  Combined PSS with two helix snakes and solenoid with field=const . S. Nikitin, IJMP A, Vol. 35, 2041001 (2020)

VEPP-4M experiments on
crossing the spin-betatron resonance sequence (ν_x=7.54, ν_y=8.58)

Energy MeV	Resonance sequence	Rate MeV/s	Polarization loss %
1948 1965	$13-\nu_y$ $12-\nu_x$	13 13	50
1948 1965 2001 2018	$13-\nu_y$ $12-\nu_x$ ν_x-3 ν_y-4	13 13 21 21	100

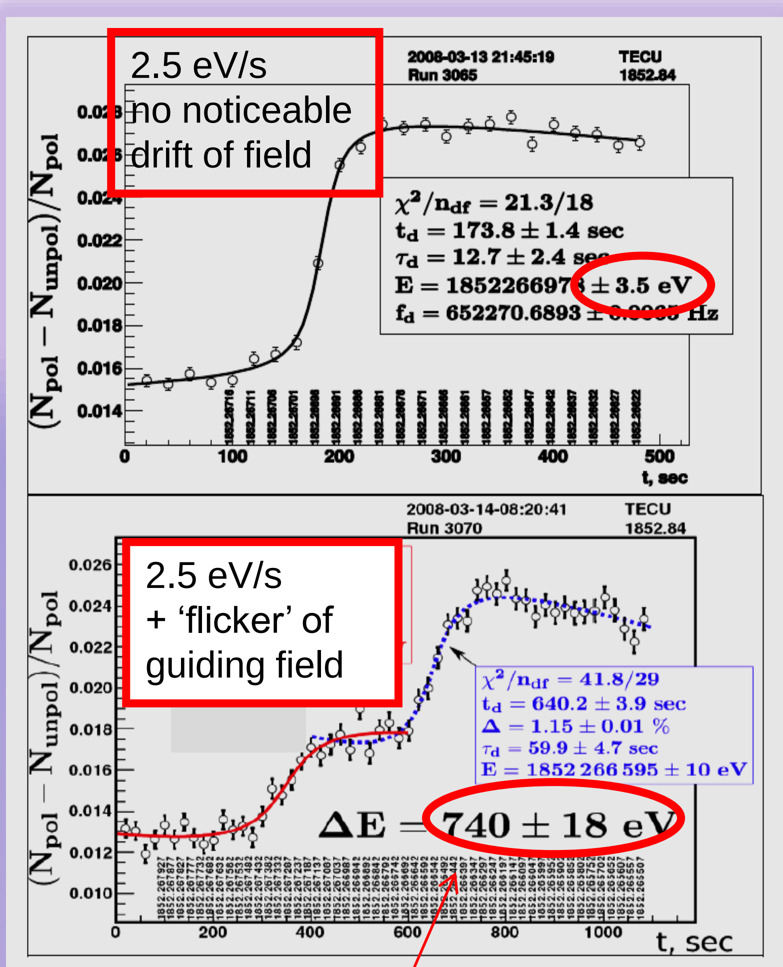
Seemingly simple experiment

Adiabatic transformation of transverse polarization into longitudinal polarization

- transverse polarization at 1.5 GeV (from VEPP3)
- using 0.6 T KEDR field as PSS, adiabatically lower energy to integer resonance ν=3 (1.32 GeV)
- thus obtain longitudinal polarization in KEDR with lifetime about 20 min (S-T time is about 400 h)
- observe longitudinal polarization with laser polarimeter

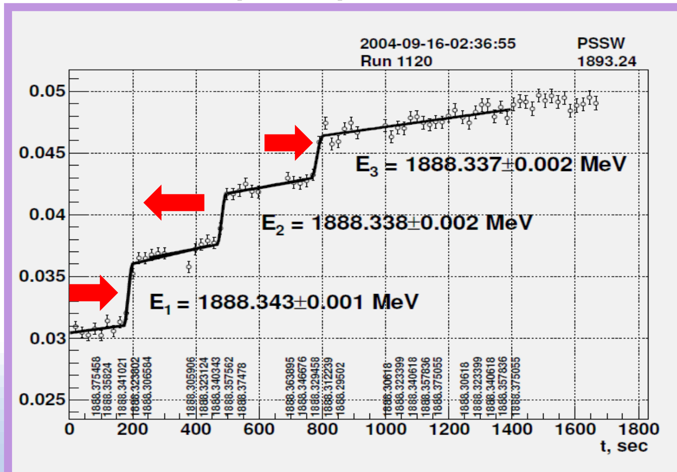
Study of features of Resonant Depolarization application

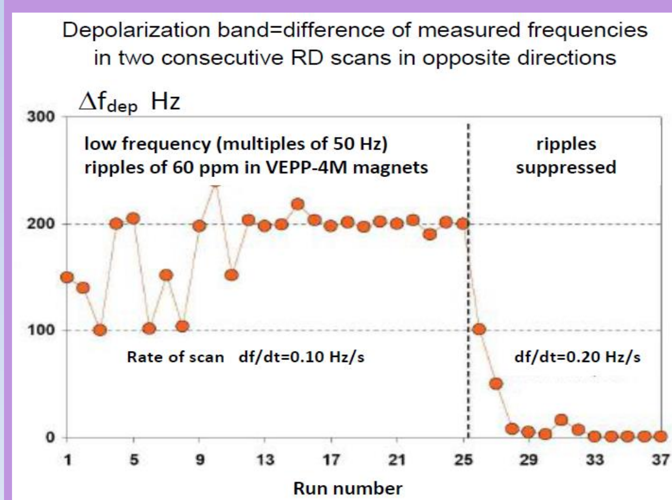
Scanning with record resolution in depolarization frequency of $2{\cdot}10^{-9}$



Influence of irregular drift (flickering) of guiding field

Thrice-repeated partial depolarization
All three measured energy values are in the 6 keV interval ($3{\times}10^{-6}$) due to field drift





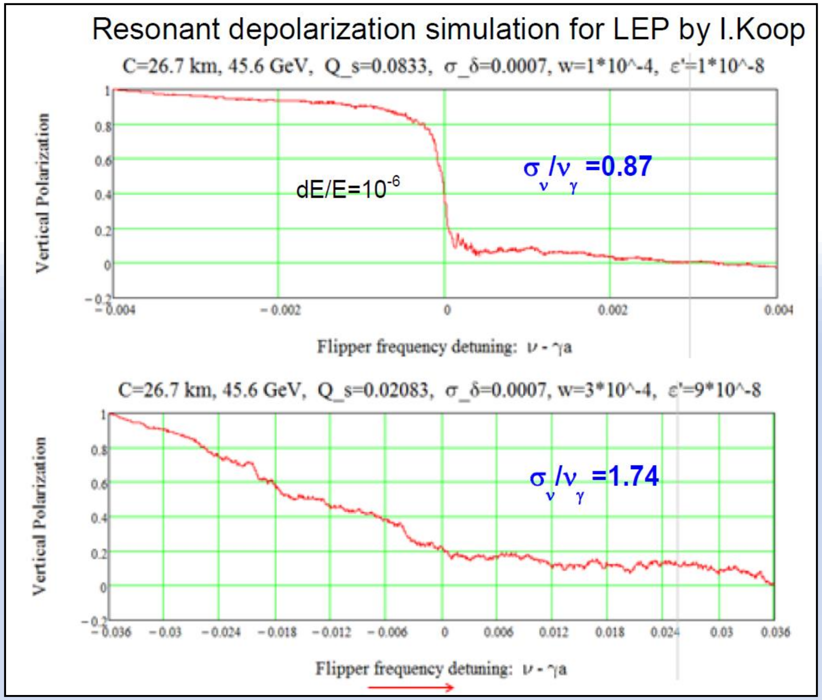
Influence of ripples in power supply sources

Issue of modulation index in RD technique

Numerical simulation of RD process by I. Koop:

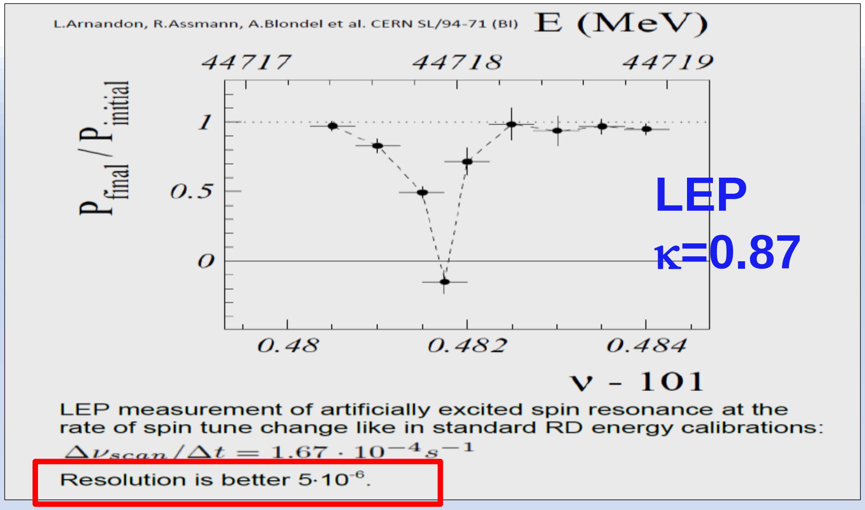
at large modulation index $\kappa = \frac{spin\ tune\ spread}{synchrotron\ tune} = \frac{\sigma_\nu}{\nu_\gamma} \geq 1$,

RD jump is not rigid (becomes "long-drawn"), accuracy may drop!



Modulation index and achieved maximum RD absolute accuracy/resolution

	κ	E	max absolute accuracy/resolution
VEPP-4M	~ 0.1 ≥ 1	1.5-1.9 GeV 4.5	$10^{-6}/10^{-9}$
FCCee	1.6 2.4	45 80	
CEPC	1.4 3	45 80	
LEP	0.87	45	$/5{\cdot}10^{-6}$



In principle, the study of this effect at VEPP-4M with κ≥1 is possible, since we have recently begun experiments on obtaining radiation polarization and using RDs at the energy of Upsilon resonance.

Summary

- Estimate of resonant spin diffusion is based on simplified model. Numerical simulation is needed. Need to try a scaling experiment
- The same should be done for fan polarization despite negative result of “Pulsar”
- At VEPP-4M, we started experiments on crossing spin resonances with application of the Partial Siberian Snake technique. Results may be useful for studying possibility of accelerating polarized beams in a booster of future lepton colliders
- At VEPP-4M at high energy, in principle, it is possible to study the features of RD, which are characteristic of the future lepton colliders

The parameters of VEPP-4M beam experiments on polarization issues may not in all correspond to the conditions in the future colliders. But identifying the features that depend on these differences while comparing experiment with theory may be useful for FCCee polarization program

Thank for attention!