On polarization and energy calibration in e+e- colliders

Sergei Nikitin

BINP, Novosibirsk

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Let me recall

some moments in the history of radiation polarization,

methods for measuring polarization and

peculiarities of its use for calibrating particle energy;

give examples from world experience,

some theses on polarization issues in new projects;

tell about some polarization experiments at VEPP-4M

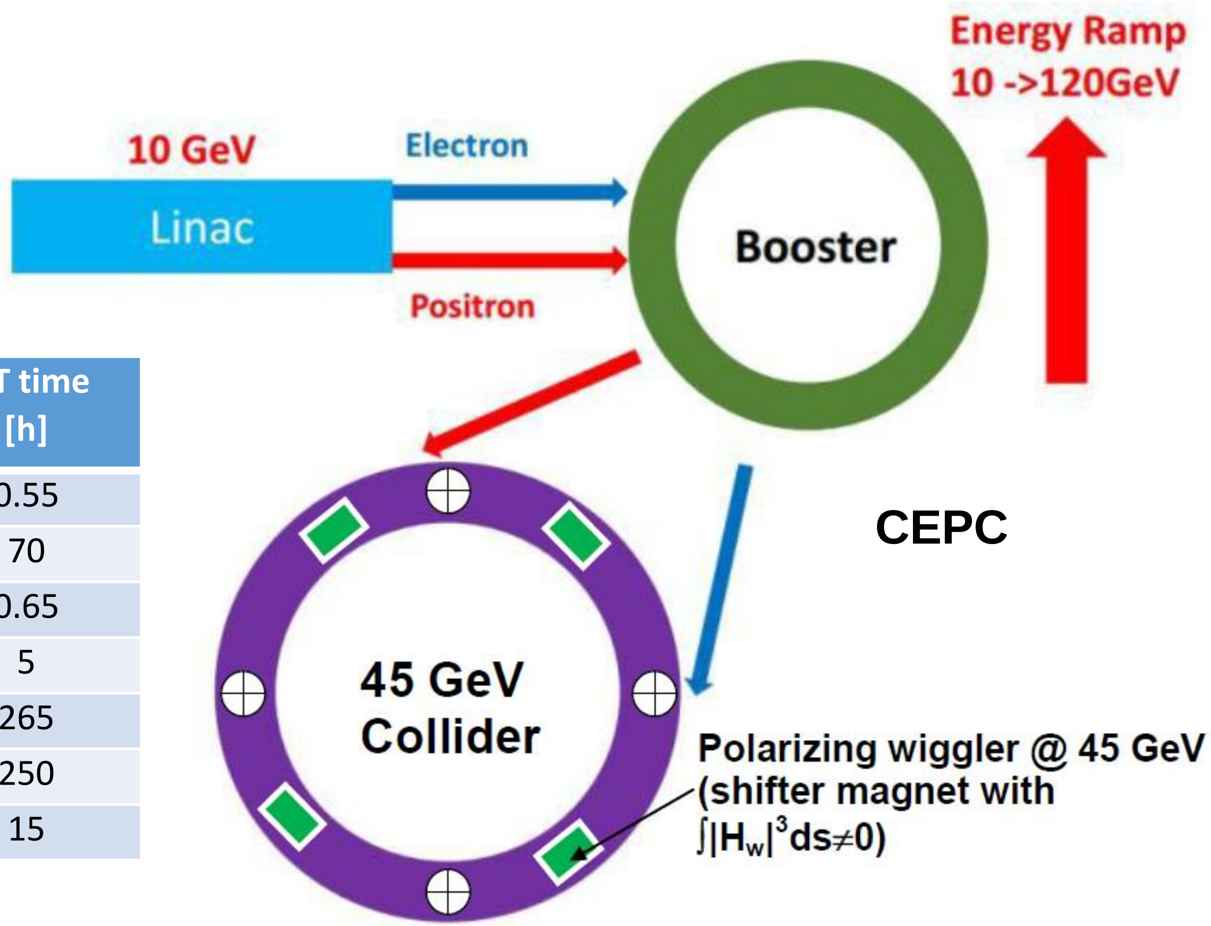
Early milestones

1963. A.A. Sokolov, I.M. Ternov. Discovery of radiative polarization in theory
1963. Discovery of Touschek effect in Orsay (France) at AdA created in INFN (Frascati).
1968. V.N. Baier, V.A. Khose (INP, Novosibirsk). Touschek scattering and then (1969) Compton scattering of circularly polarized optical photons proposed for measuring polarization.
1970. First observation of radiative polarization at VEPP-2M, 625 MeV (INP, Novosibirsk). First application of Resonant Depolarization (at external resonance). Touschek detector used.
1970. First observation of radiative polarization at ACO, 536 MeV in Orsay (France). Touschek detector used. Enforced depolarization at betatron-frequency-sideband resonances.
1970. With article on motion of spin in storage ring with arbitrary field and polarization direction (DAN USSR) the series of fundamental works by Ya.S. Derbenev and A.M. Kondratenko began.
1975. Resonant Depolarization proposed to measure beam energy (INP, Novosibirsk). Used to measure ϕ-meson mass.
1975. First measurement of polarization using laser polarimeter (SPEAR 2.4 GeV at SLAC).
1983. First observation of spin dependence of SR intensity and its application to measure polarization (VEPP-4 at 5 GeV, INP, Novosibirsk).
1994. First production of longitudinal polarization in high energy electron storage ring HERA 27.5 GeV; spin rotators with transverse magnetic fields used

Sokolov-Ternov polarization time

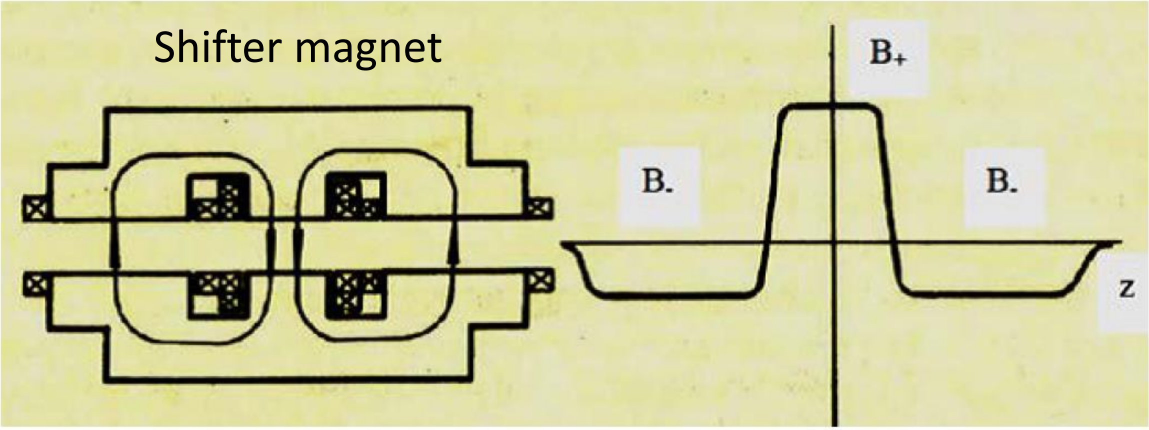
$$\tau_p = \left[\frac{5\sqrt{3}}{8} \frac{r_e \lambda_e \gamma^5}{R^3} \langle | K |^3 \rangle \right]^{-1}$$

	Energy [GeV]	S-T time [h]
VEPP-3	1.85	0.55
VEPP-4M	1.85	70
VEPP-4M	4.73	0.65
LEP	45	5
CEPC	45	265
FCCee	45	250
CEPC	80	15



Long-known tool: special wigglers amplify polarizing effect of storage ring field!

Special wigglers to speed up polarization at CEPC



N_w	B_+ T	L_+ m	B_- T	L_- m	$\frac{\tau_p}{\tau_p^w}$	u	$\frac{\Delta E_w}{\Delta E}$
10	0.5	1	0.125	2	8.3	0.20	2.6
10	0.6	1	0.15	2	13.6	0.29	3.3

Calculated for a variant of the CEPC-Z magnetic structure

Requirements to fields :

$$\int B_w d\vartheta = 0, \quad \int B_w^3 d\vartheta \neq 0, \quad |B_+|^3 >> |B_-|^3$$

Decrease of polarization time:

$$\tau_p^w = \tau_p \left[1 + N_w \frac{B_+^3 L_+ + 2|B_-|^3 L_-}{2\pi R \langle B_0 \rangle B_0^2} \right]^{-1}$$

Fraction of radiation energy loss enhancement :

$$u = N_w \frac{B_+^2 L_+ + 2B_-^2 L_-}{2\pi R \langle B_0 \rangle B_0}$$

Harmful effect is increase in beam energy spread:

$$\frac{\Delta E_w}{\Delta E} = \left[\frac{\tau_p}{\tau_p^w} \cdot \frac{1}{1+u} \right]^{1/2}$$

While using laser polarimeter for RD technique it is enough to ensure polarization degree about of 10% achived in a few hours with shifter magnets

Perfect relation of spin tune and particle energy for RD

No horizontal and longitudinal magnetic fields as well as vertical electric fields

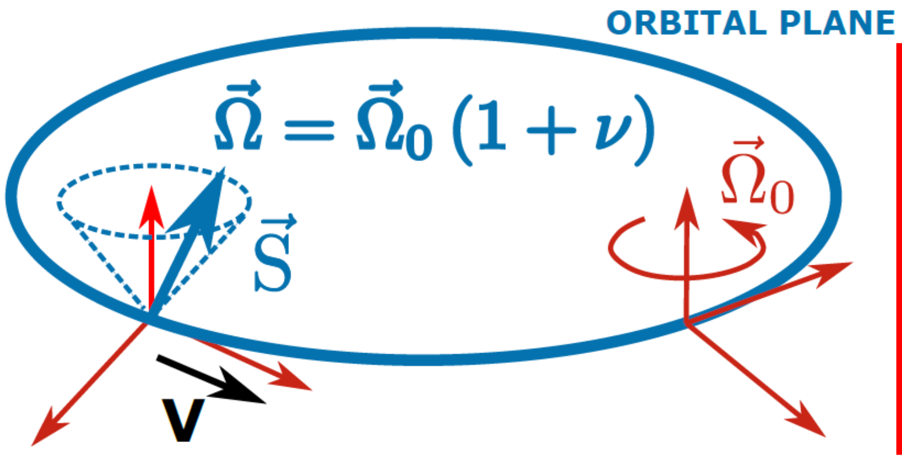
Perfect case - strictly flat orbit

$$\omega = \langle\Omega\rangle = \frac{e}{2\pi mc}\left(\oint \frac{B_\perp}{\gamma}\, d\theta + a \oint B_\perp\, d\theta\right) = \omega_0 \left(1 + \frac{a}{mc^2}\langle E\rangle\right)$$

$$\langle E\rangle = \frac{eR}{2\pi}\oint B_\perp\, d\theta$$

$\omega = \langle \Omega \rangle$ spin precession frequency

$\omega_0 = \frac{c}{R} = \langle\Omega_0\rangle$ revolution frequency



$$\langle E\rangle = \left(\frac{\omega}{\omega_0} - 1\right)\left(\frac{g-2}{2}\right)^{-1} mc^2 = \nu \cdot 440.6484587(27) \quad \text{MeV}$$

$\nu = \gamma\left(\frac{g-2}{2}\right) = \gamma a$ spin tune

enforced depolarization at spin resonance $\nu\omega_0 + \omega_d = k\omega_0$

ω_d frequency of external electromagnetic field

The difference between the spin precession and the Larmor precession of velocity.

To determine the absolute beam energy in a storage ring with a flat orbit it is enough to measure a ratio between the spin frequency ($\nu\omega_0$) and the revolution one (ω_0) given by the RF frequency. The relative accuracy is limited by the uncertainty in the fundamental constant values and equals to **$6.1 \cdot 10^{-9}$**.

Radiative polarization in real storage ring

Derbenev-Kondratenko theory

Depolarization factor due to field imperfections

$$G = \frac{\langle K^3 \rangle}{\left\langle |K|^3 \left(1 + \frac{11}{18}\vec{d}^{\,2}\right) \right\rangle} \le 1 \,, \qquad (K\text{, orbit curvature}),$$

reduces polarization degree (P) and relaxation time of radiative polarization (τ_{rel})

$$\boxed{P = G \cdot P_0 \,. \quad P_0 = \frac{5\sqrt{3}}{8} = 0.92 \,, \quad \tau_{rel} = G \cdot \tau_p \,,}$$

$\vec{d} = \gamma \dfrac{\partial \vec{n}}{\partial \gamma}$ periodical with azimuth spin-orbit coupling function

(equilibrium axis of precession $\vec{n}$ depends on energy)

Disturbances of the vector $\vec{n}$ and the magnitude of the spin-orbitcoupling $\gamma d\vec{n}/d\gamma$ increase in the vicinity of the spin resonances:

integer

$\nu = \nu_k = k$;

spin-betatron

$\nu_k = p\nu_x + q\nu_y + k$;

modulation resonances with synchrotron tune ν_γ

$\nu_k = k + m\nu_\gamma$.

Sources are vertical closed orbit distortions, rolls of quadrupoles, solenoids and non-linearity.

"Shake" of precession axis ***n*** due to quantum fluctuations→ **"non-resonant" spin diffusion** growing nearby spin resonances, main depolarization factor in storage rings as long as spin tune spread is much less than distance to closest dangerous resonances

Depolarization factor with synchrotron modulation

Radial magnetic and vertical electric fields cause most strong depolarization effect which relates to integer spin resonances $\nu = \gamma a = k$ (ν, spin precession tune). **Kondratenko's** formula for depolarization factor takes into account spin tune modulation by synchrotron oscillations with frequency ν_γ:

$\boxed{G=P/P_0=P/0.92}$

$$G \approx \left\{1 + \frac{11\nu^2}{18}\sum_{k,l}\frac{|w_k|^2\, I_l(\sigma_\nu^2/\nu_\gamma^2)\exp(-\sigma_\nu^2/\nu_\gamma^2)}{\left[\left(|\nu-k|-l\nu_\gamma\right)^2-\nu_\gamma^2\right]^2}\right\}^{-1}$$

$w_k \approx \left\langle \frac{\nu}{R}\frac{d^2 y_0}{d\vartheta^2}\exp(-ik\vartheta)\right\rangle$, resonant harmonic amplitude in case of vertical closed orbit distortions (y_0);

l, order of sideband resonance $\nu \pm l\cdot\nu_\gamma = k$;

$\sigma_\nu = \nu\sigma_\gamma$, instant spin tune spread due to energy spread σ_γ;

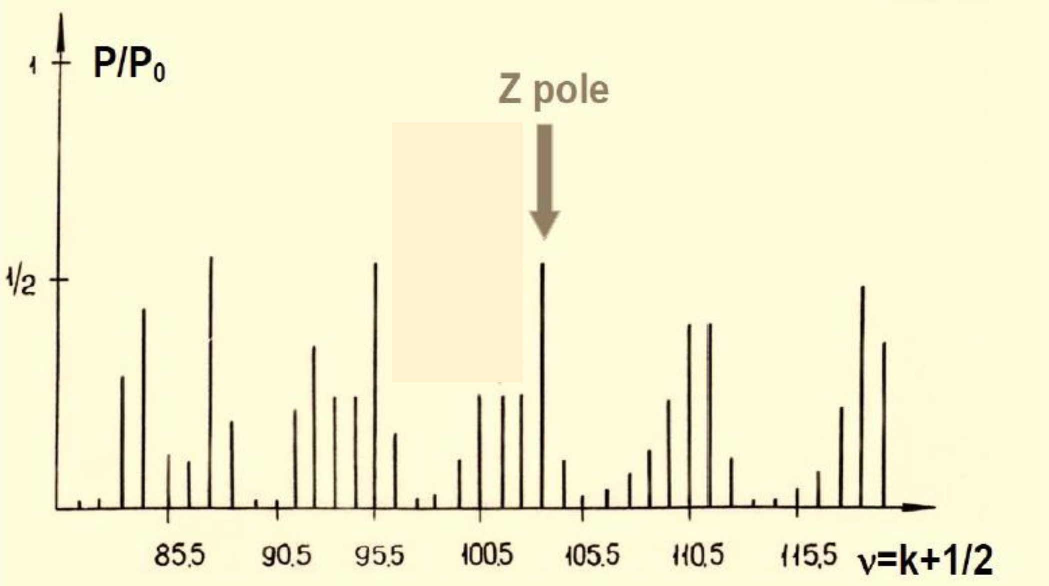
$I_l(x)$, modified Bessel function.

$\boxed{\kappa = \frac{\sigma_\nu}{\nu_\gamma} \text{ is index of modulation;}}$

Equation for G is valid if $\sigma_\nu^2\Lambda_\gamma << \nu_\gamma^3$; Λ_γ is the radiation decrement of synchrotron oscillations in inverse turns.

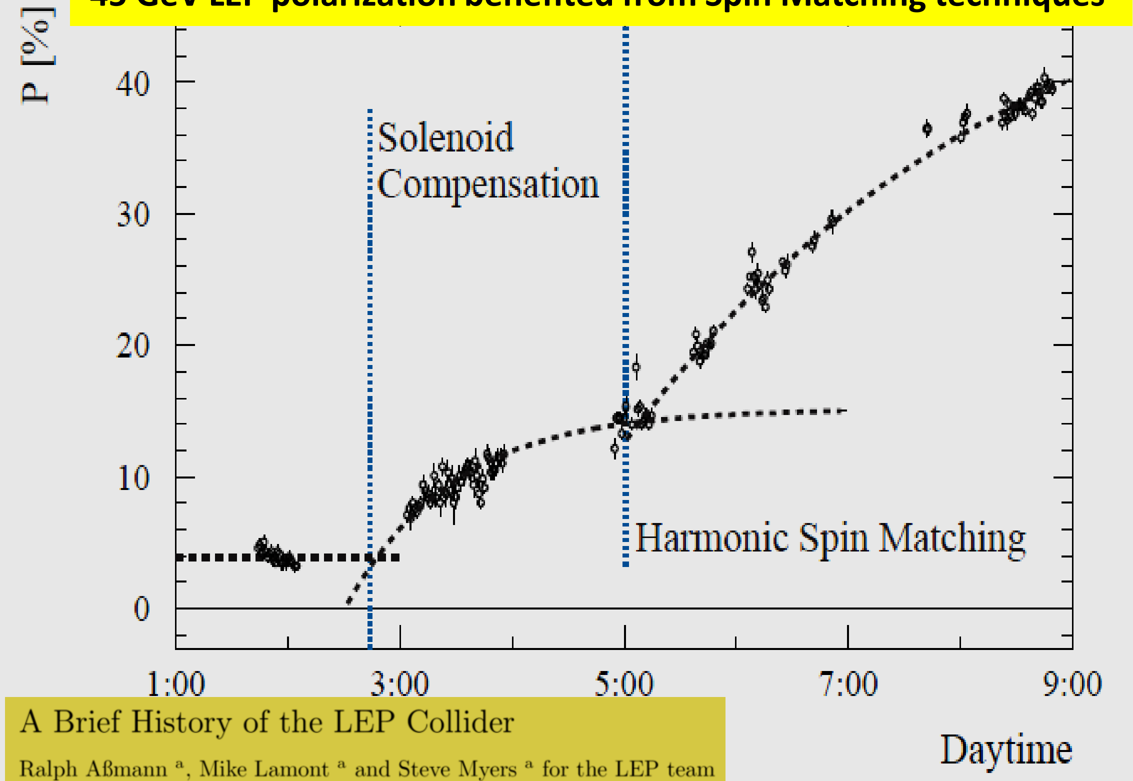
Expectations vs observation: LEP experience

S.A.Nikitin, E.L. Saldin, M.V. Yurkov/NIM A 216 (1983) 317-328



Expected equilibrium polarization degree in LEP of Blue Book design (1978) for one of realization of random vertical displacements of quadrupoles (RMS=50 microns, closed orbit RMS distortion=3 mm) vs half-integer values of spin tune.

45 GeV LEP polarization benefited from Spin Matching techniques



A Brief History of the LEP Collider

Ralph Aßmann [a], Mike Lamont [a] and Steve Myers [a] for the LEP team

[a]CERN, Geneva 23 CH-1211, Switzerland

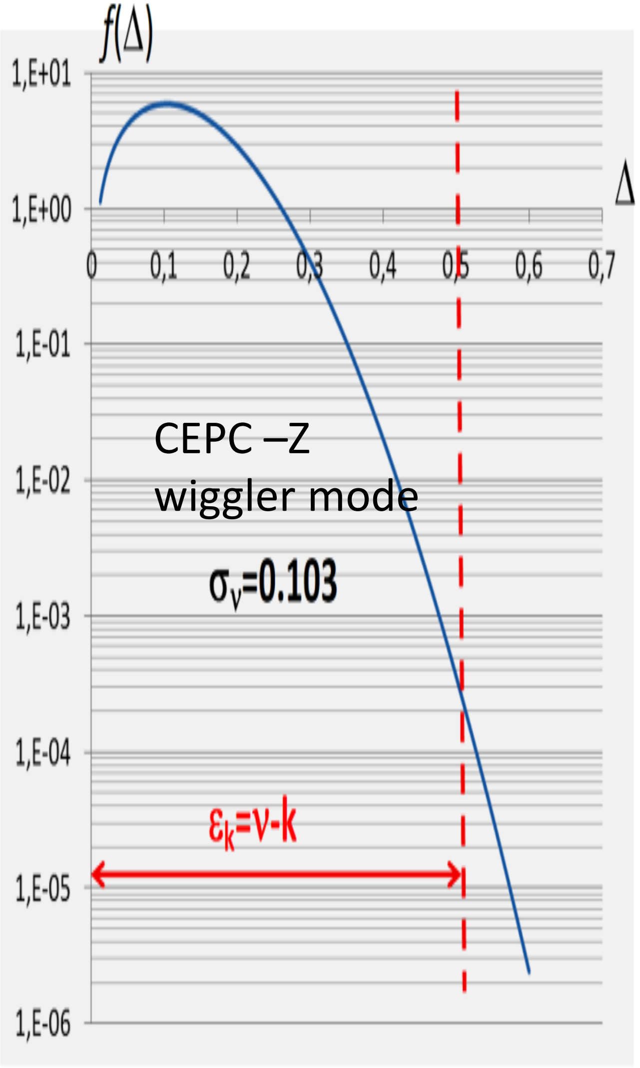
It is important to reduce the resonant harmonic amplitudes in orbit distortions down to level $|w_k| \leq 10^{-3}$ using special orbit bumps or global correction. There was positive experience of LEP team: polarization was improved to more than 35 % with average around 50% using Harmonic Spin Matching technique (R. Assmann , A.Blondel et.al., CERN SL/94-62 (AP)

Resonant diffusion of polarization due to large spin tune spread

It was not so relevant in electron-positron rings of previous generations.

Resonant diffusion due to large instant spin tune spread (σ_ν~0.1 in wiggler mode or at higher energy) 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



S. Nikitin, "Polarization issues in circular electron–positron super-colliders", Int. J. Mod. Phys. A, vol. 35, no. 15n16, p. 2041001, 2020.

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

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

$f(\Delta) = \Delta \cdot \exp\left(-\Delta^2 / 2\sigma_\nu^2\right) / \sigma_\nu^2$ 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

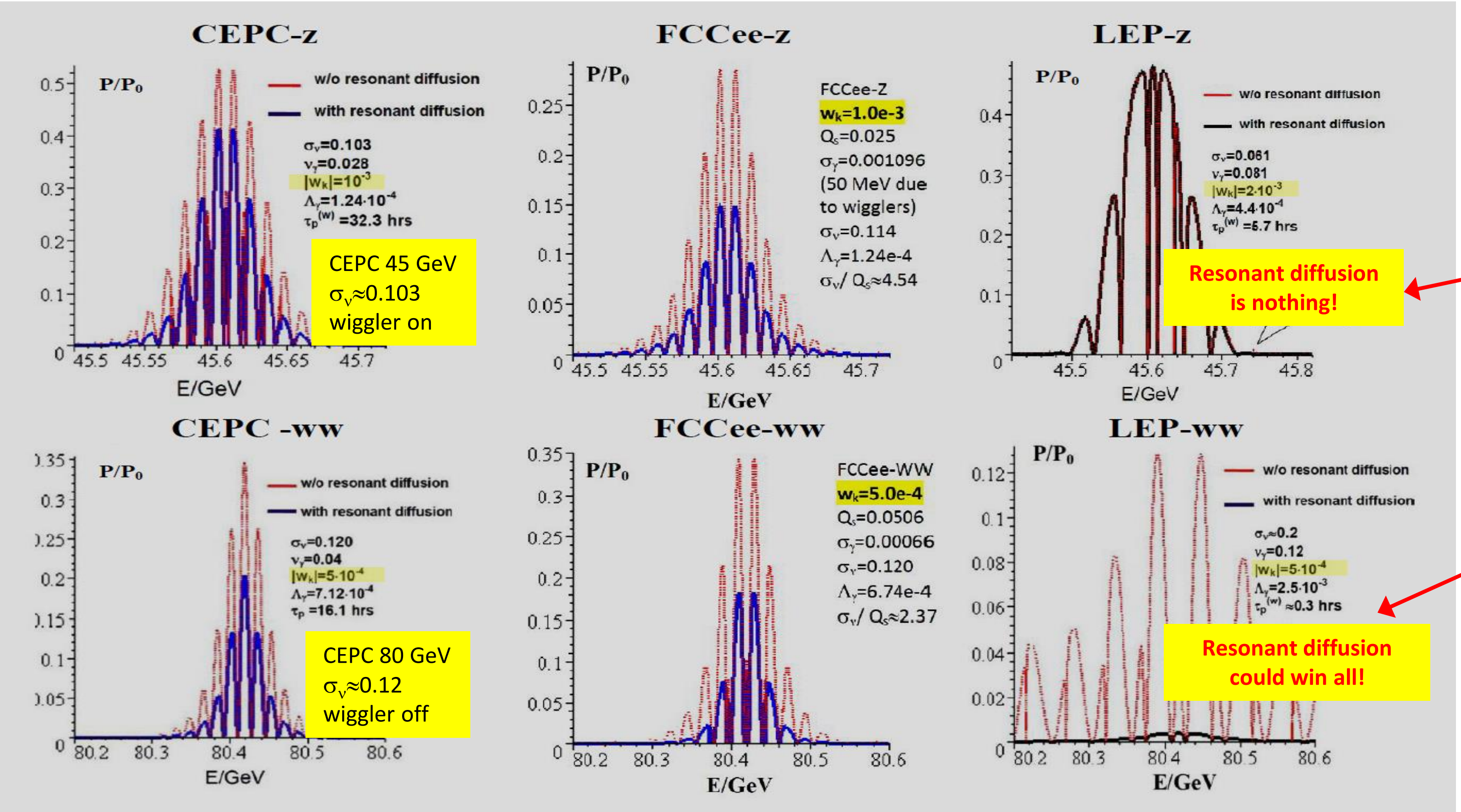
Resonant diffusion rate in approximation of fast crossings:

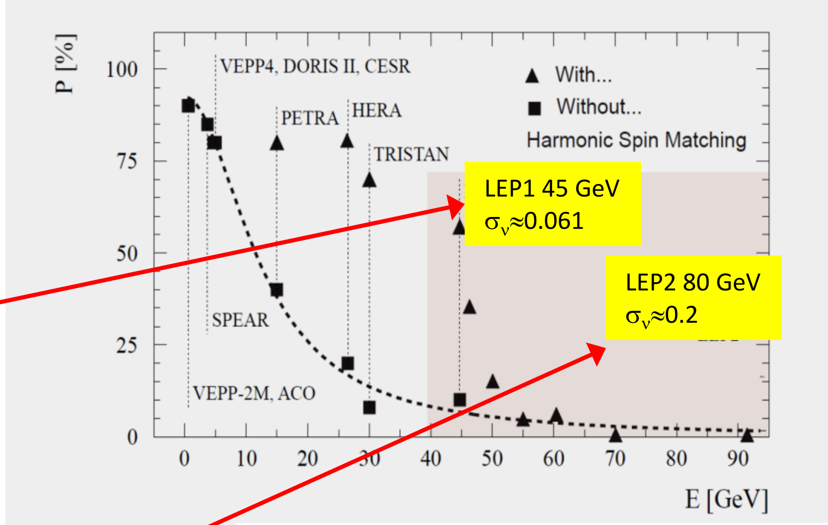
$$\boxed{\frac{1}{\tau_{res}} \approx 2\pi f_0 \frac{|w_k|^2}{\sigma_\nu^2} \int_{\varepsilon_k}^{\infty} \frac{\Delta \cdot e^{-\frac{\Delta^2}{2\sigma_\nu^2}}}{\sqrt{\Delta^2 - \varepsilon_k^2 + (\sigma_\nu \Lambda_\gamma / \nu_\gamma)^2}} d\Delta}$$

Calculation: large spin tune spread σ_ν~ 0.1 can be noticeable depolarizing factor!

Combined effect of non-resonant and resonant diffusions

S. Nikitin, "Polarization issues in circular electron–positron super-colliders," Int. J. Mod. Phys. A, vol. 35, no. 15n16, p. 2041001, 2020.





A Brief History of the LEP Collider

Ralph Aßmann[a], Mike Lamont[a] and Steve Myers[a] for the LEP team

[a]CERN, Geneva 23 CH-1211, Switzerland

Figure 10. Maximum observed levels of polarization versus beam energy for different electron storage rings. The polarization level is indicated with (triangle) and without (square) Harmonic Spin Matching.

Note, the attempts to get a polarization at 80 GeV LEP failed!

Spin tune spread in CEPC, FCCee at 80 GeV is about 2 times smaller than that in LEP. Calculation: there is chance to obtain relevant polarization in 80 GeV CEPC , FCCee if dangerous spin harmonics in CO distortions are suppressed to level of 5e-4 and below

Methods to measure beam polarization in e+e- storage rings

- Polarimeter based on Intra-Beam Scattering (IBS)

  VEPP-2, ACO, VEPP-2M, VEPP-4, VEPP-4M …

- Compton polarimeters:

  Laser polarimeter **(supposed for CEPC, FCCee)**

  SPEAR (1976), DESY, VEPP-4, LEP

  Scattering of SR by an opposed beam

  VEPP-4 (1982)

- Spin Light based polarimeter **(interesting, in my opinion, to consider for CEPC, FCCee)**

  VEPP-4 (1983)

- Møller polarimeter based on internal polarized target

  VEPP-3 (2003)

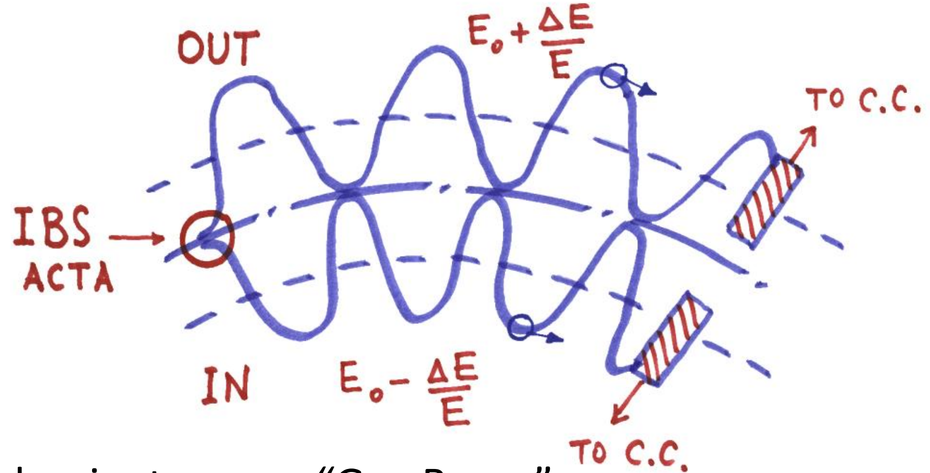
Basics of Touschek polarimeter

IBS cross section decreases with polarization ($\zeta \neq 0$)

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

$$\frac{d\sigma_0}{d\Omega} = \frac{r_0^2}{4\beta^4} \left[\frac{4}{\sin^4\theta} - \frac{3}{\sin^2\theta} \right], \qquad \beta = \frac{v}{2c} = \frac{v_1 - v_2}{2c}$$

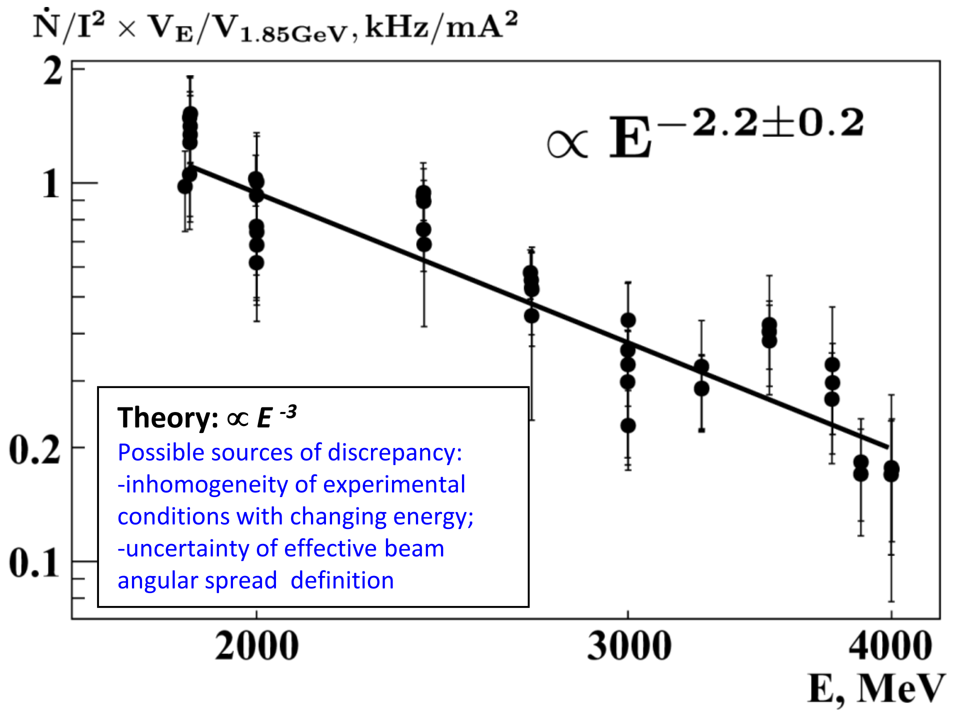
Schematic diagram of Touschek particles detecting



If IBS dominates over “Gas-Beam” one can use a sum of the counter rates instead of their logical production

S. A. Nikitin and I. B. Nikolaev, JETP, vol. 115, no. 1, pp. 36–47, 2012

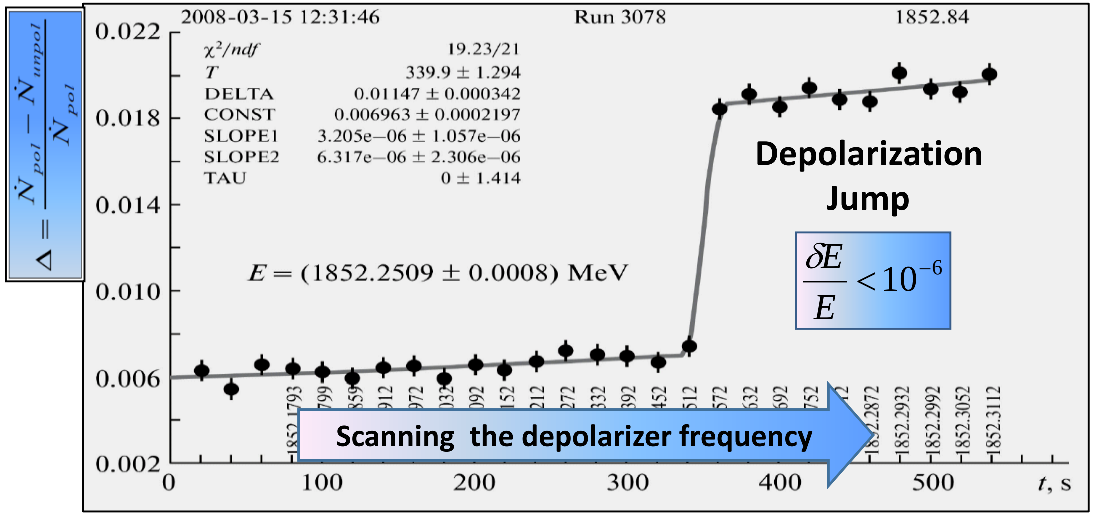
1. IBS electron count rate normalized on beam volume and on squared current vs VEPP-4M beam energy

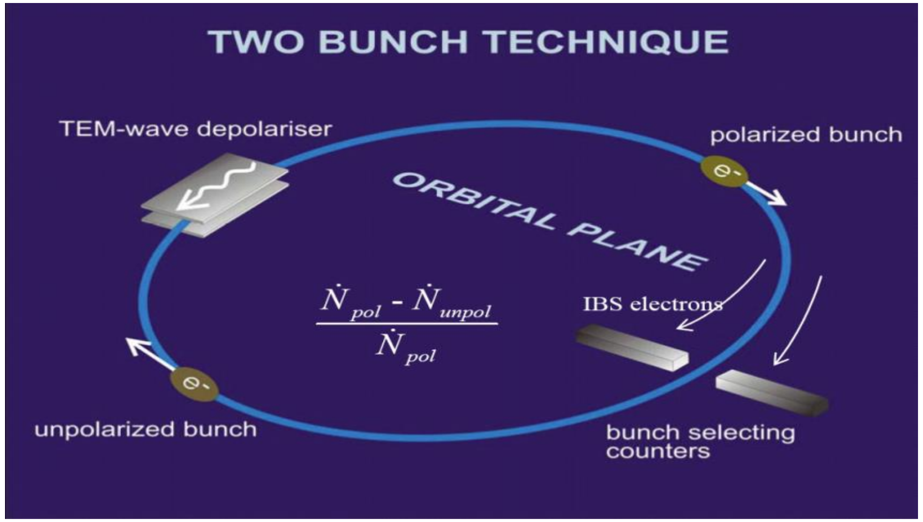


2. Polarization effect in count rate of Touschek particles decreases with energy as $\propto 1/E^4$

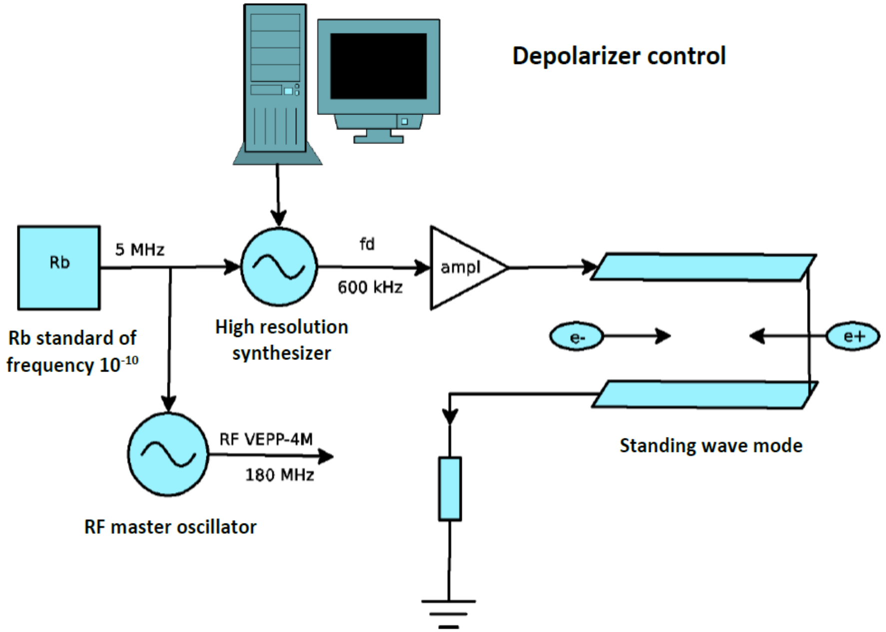
Touschek polarimeter in use for RD at VEPP-4M works very well at E_{beam} <2 GeV but will be rather not effective at E_{beam} > 4 GeV because of considerable decrease of effect and counting rate with energy

RD energy calibration using Touschek polarimeter at VEPP-4M





- RB standard, common for VEPP-4M RF master oscillator and for depolarizer synthesizer, practically excludes their relative drift! RD method accuracy is determined by ratio of depolarization and revolution frequencies.
- Revolution frequency stability $\frac{\Delta\omega_0}{\omega_0} \sim 10^{-10}$ corresponds to energy stability $\frac{\Delta E}{E} = \alpha^{-1}\frac{\Delta\omega_0}{\omega_0} \approx 6\cdot 10^{-9}$, $\alpha = 0.017$ mom.comp. factor. Important for long-term stability of energy in experiment
- At CEPC and FCCee , required stability of reference signal $\sim 10^{-11}$ for providing accuracy $\frac{\Delta E}{E} \sim 10^{-6}$ $(\alpha \sim 10^{-5})$.



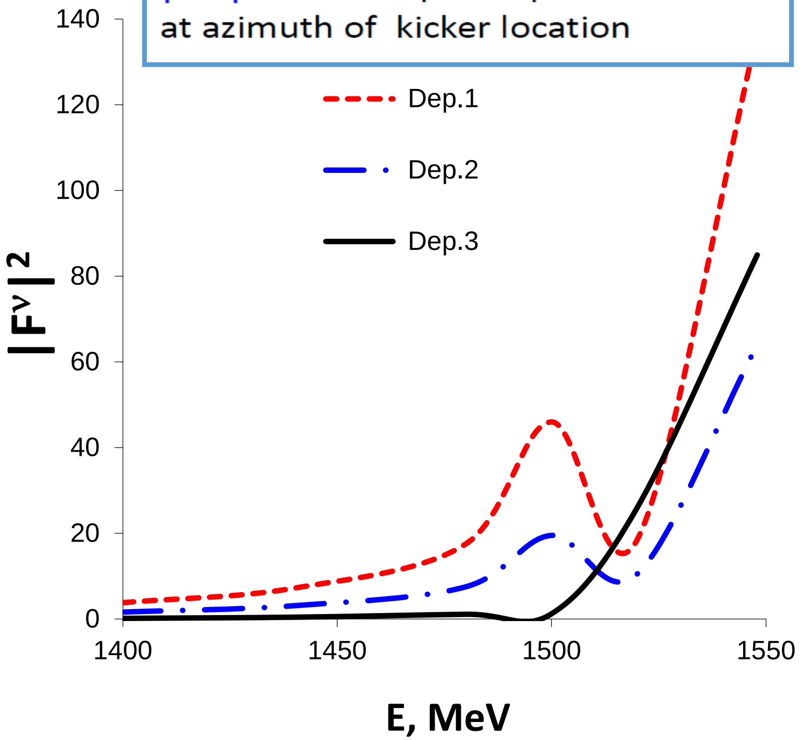
In the special "fine scan" mode, we achieve a record resolution of 10^{-9}

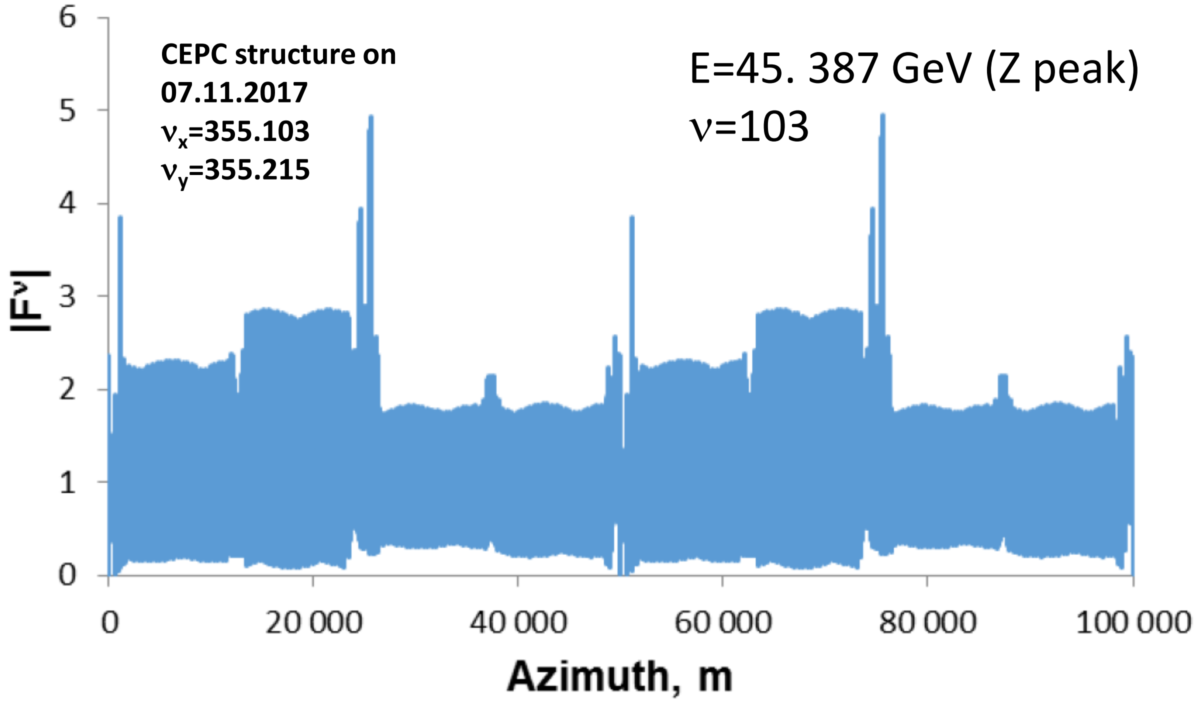
Spin response factor of kicker-depolarizer

Depolarization rate due to kicker-depolarizer (strip-line based):
$\tau_{RD}^{-1} \propto U^2 |F^\nu|^2$
U voltage amplitude at kicker plates
$|F^\nu|$ value of spin response function at azimuth of kicker location

$$F^{\nu} \approx \frac{\nu \cdot e^{i\nu\theta}}{2}\left\{\left[1-e^{\frac{i2\pi}{m}(\nu+\nu_z)}\right]^{-1} \cdot f_z \int_{\theta-\frac{2\pi}{m}}^{\theta} K f_z^{*\prime} e^{-i\nu\Phi} d\theta' - \left[1-e^{\frac{i2\pi}{m}(\nu-\nu_z)}\right]^{-1} \cdot f_z^{*} \int_{\theta-\frac{2\pi}{m}}^{\theta} K f_z^{\prime} e^{-i\nu\Phi} d\theta'\right\}$$

Introduced in: Y. S. Derbenev, A. M. Kondratenko, and A. N. Skrinsky, Part. Accel., vol. 9, p. 247, 1979.





Factor $|F^\nu|$ can enhance or weaken significantly the direct action of the depolarizer, depending on the azimuth of its placement and the energy. Energy dependence of spin response of three different kicker-depolarizers at VEPP-4M placed at different azimuths. A special experiment at 1495 MeV revealed that the beam could be depolarized by depolarizer #1, not by depolarizer #3, all other factors being equal.

The spin response function is used to estimate the depolarizing effect of quantum fluctuations due to corresponding transverse perturbations of the guide field. Calculation of $|F^\nu|$ allows choose the optimal place for the kicker depolarizer (providing a strong effect on the spin with a weak perturbation in orbital motion).

Laser polarimeter

Cross Section of Compton Scattering (V.N. Baier, V.A. Khoze 1969):

$d\sigma = d\sigma_0 + d\sigma_1 \cdot \zeta_p \zeta_e \cdot \sin\varphi$,

ζ_p circular polarization of photons, ζ_e transverse beam polarization,

φ angle between scattering plane and plane ⊥ to electron polarization

$$n = \gamma\theta, \qquad \lambda = \frac{2\omega E}{m^2}, \quad \omega_s = \frac{2E\lambda}{1 + n^2 + 2\lambda}$$

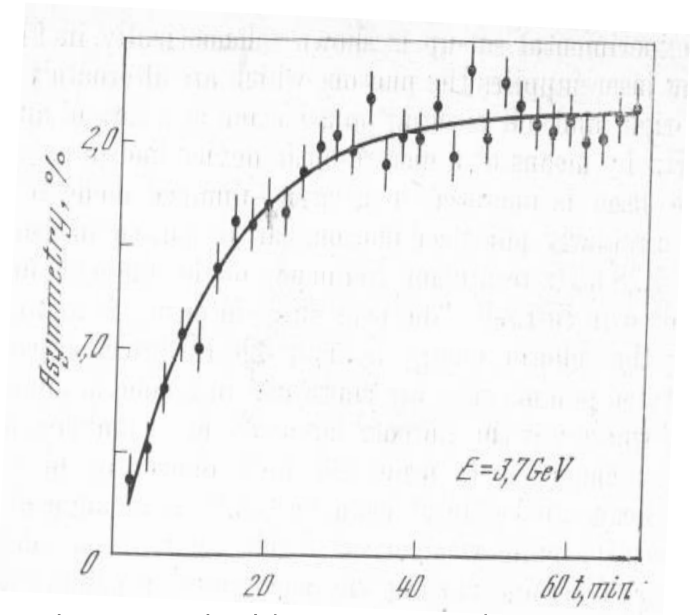
Azimuthal asymmetry:

$$A = \frac{d\sigma_1}{d\sigma_0} = -\frac{2\lambda\, n(1+n^2)}{2\lambda^2(1+n^2)+(1+n^2+2\lambda)(1+n^4)}$$

$A_{max} \approx 0.3$ at $\mathrm{n} = \lambda = 1$

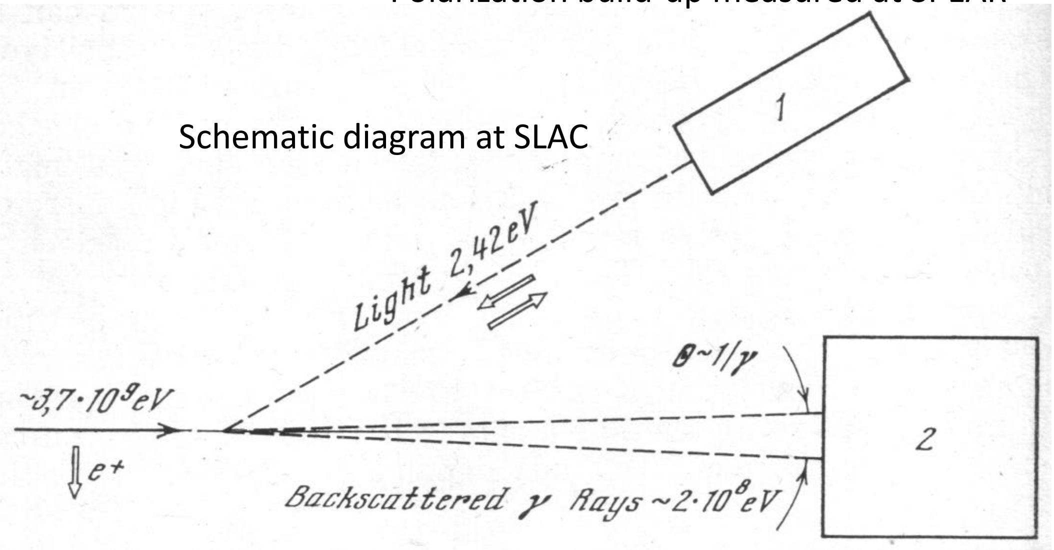
The measured quantity, proportional to the degree of polarization, is the asymmetry in the vertical distribution of Compton gamma-quanta with periodic switching of the sign of the circular polarization of the laser photons.

Higher energy to advantage!



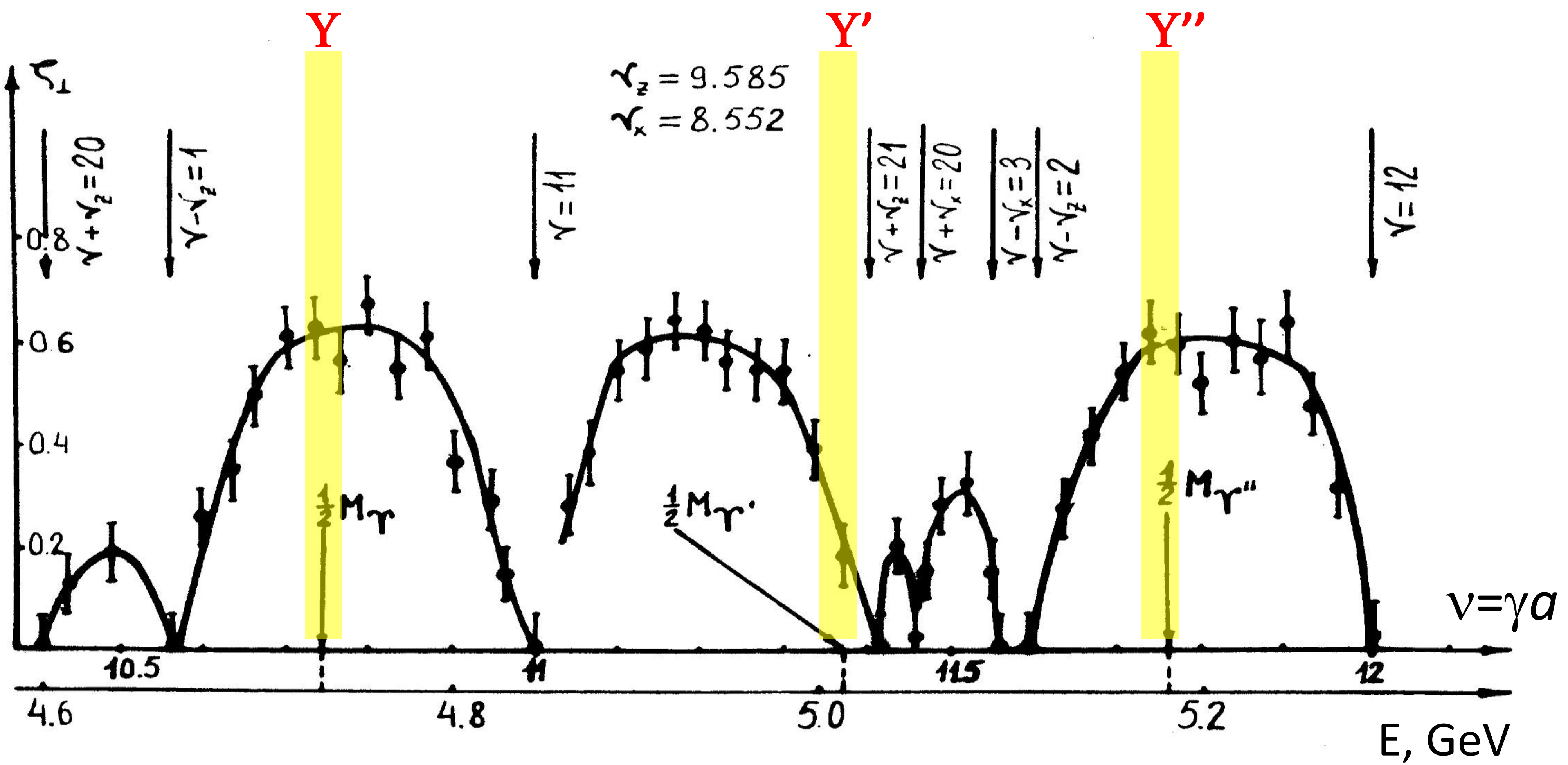
Polarization build-up measured at SPEAR

Schematic diagram at SLAC



SPEAR, VEPP-4, DORIS, PETRA, TRISTAN, CESR, HERA, LEP ….

Polarization at VEPP-4 in the region of Upsilon family (early 80s)



Measurements performed using the laser polarimeter. Prior to these measurements, the coupling correction system was modified to more than double the degree of polarization at the Υ resonance energy.

Spin dependence of SR intensity

- Interference between radiations of the electric charge and of the magnetic moment when an electron moving along curved trajectory I.M. Ternov, V.G. Bagrov& R.A. Rzaev 1964; V.N. Baier, V.M. Katkov& V.M Strakhovenko 1971; Y.S. Derbenev& A.M. Kondratenko (in a classical theory approach)_1973

$$W_s = \frac{2e^2}{m^2}\gamma^5 \left|\dot{\vec{v}}\right|^2 (\vec{v}\times\dot{\vec{v}})\vec{S}$$

- The SR power of a naturally polarized beam is larger than that of an unpolarized one. The harder spectrum the larger effect which is proportional to beam polarization ς.

Generally: $\delta = \frac{\hbar\omega_c}{m\gamma}\varsigma.$ In hard part of spectrum: $\delta = y\frac{\hbar\omega_c}{m\gamma}\varsigma,$ $\omega_c = \frac{2}{3}\frac{eH}{m}\gamma^3,$ $y = \frac{\omega}{\omega_c} \gg 1$

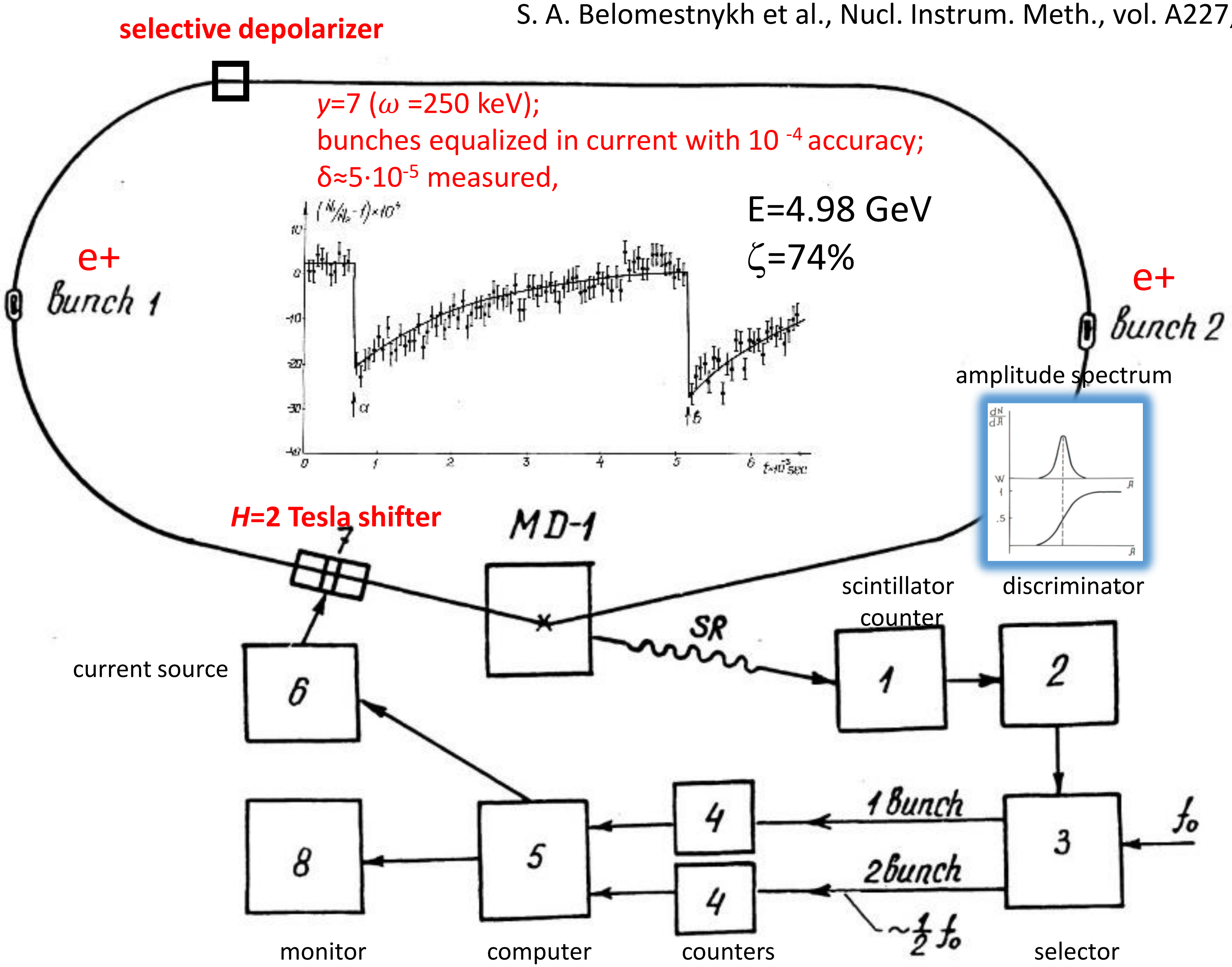
- The dependence of radiation on the direction of the spin underlies the new mechanism of polarization by Derbenev-Kondratenko due to spin-orbit coupling

$$\zeta = \frac{8}{5\sqrt{3}} \frac{< |\dot{\vec{v}}|^2 \vec{v}\times\dot{\vec{v}}(\vec{n} - \vec{d}) >}{< |\dot{\vec{v}}|^3 [1 - \frac{2}{9}(\vec{n}\cdot\vec{v})^2 + \frac{11}{18}\vec{d}^2] >}.$$

- For example, a strong magnet at azimuth, where ***n***·***H*** = 0 but ***d***·***H***≠0 , can help with longitudinal polarization schemes.

First observation of Spin Light (VEPP-4, 1983)

S. A. Belomestnykh et al., Nucl. Instrum. Meth., vol. A227, pp. 173–181, 1984



The quantum effect ~ 10^{-4} has been measured, in fact, based on the classical concept of a particle as an elementary magnet. Thus, a positive answer was given to previously considered controversial (N. Bohr) issue, highlighted in a 1930 article by W. Pauli, about the possibility of setting up experiments on the study of the spin properties of free (not bound in an atom) electrons, in particular, when they move in a macroscopic magnetic field. This is how our result was assessed by I.M. Ternov and V.V. Mikhailin in the book "Synchrotron Radiation. Theory and experiment ", 1988.

Effect grows with increase in magnetic field, particle energy and energy of registered gamma quanta!

Mass measurement experiments with RD

ϕ OLYA, VEPP-2M, 1978

$K^{\pm}$ EMUL, VEPP-2M, 1979

J/Psi, Psi' OLYA, VEPP-4, 1980

Υ MD-1, VEPP-4, 1982; CUSB, CESR, 1984

Υ' MD-1, VEPP-4, 1982; ARGUS, DORIS, 1984

Υ'' MD-1, VEPP-4, 1983-1984

Z ALEPH etc., LEP, 1991

J/Psi, Psi' KEDR, VEPP-4M, 2003

t KEDR, VEPP-4M, 2007

Particle Mass Accuracy Top List

Particle	$\Delta m/m$, *ppm*
n	0.04
p	0.04
e	0.04
μ	0.09
$\pi^{\pm}$	2.5
J/ψ	3.5
ψ'	3.9
π^0	4.5

Issues on mass measurement accuracy

1. **Groups of error sources**

- **mean energy value determination basing on measured spin frequency**
- energy stability in time domains between energy calibrations
- determination of produced particles energy in a Center-of-Mass system basing on energy of one of colliding beams measured with RD

2. **Methods of accounting**

- correction of measurement data
- declaration of uncertainty

3. **Sources of errors**

- **radial orbit distortions** *(non-stability of currents in magnet coils, temperature variations, geomagnetic storms, solar and lunar daily geomagnetic variations…)*
- **violation of simple energy-spin tune relation** *(random perturbations of vertical orbit, weak longitudinal magnetic fields, vertical orbit bumps at sections with bend magnets… and the like)*
- **azimuthal dependence of beam energy due to radiation losses**
- **effect of beam parameters in IP** *(momentum spread, inaccurate colliding beam convergence, parasitic vertical dispersion, FF chromaticity, beam potential…)*

In red: issues concerning RD method

Example with imperfect "spin tune- energy" relation

Vertical distortions and torsions of closed orbit

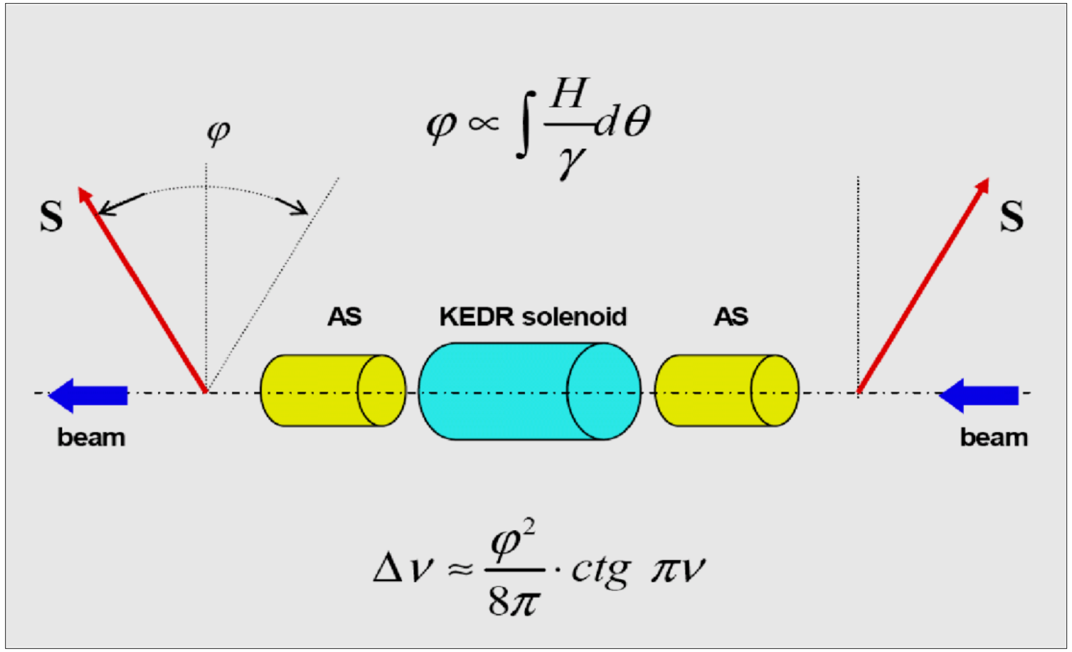
Thomas-BMT equation "works" in full form:

$$\boldsymbol{\Omega} = -\left(\frac{q_0}{\gamma} + q'\right)\boldsymbol{B} + \frac{q'(\gamma-1)}{\gamma v^2}\boldsymbol{v}(\boldsymbol{v}\cdot\boldsymbol{B}) + \left(\frac{q_0}{\gamma+1} + q'\right)\boldsymbol{v}\times\boldsymbol{E}$$

Direct proportionality relation "energy-spin tune measured with RD" violated:

$$\nu' \approx \gamma a + \Delta\nu\ (perturbations,\ energy\ )$$

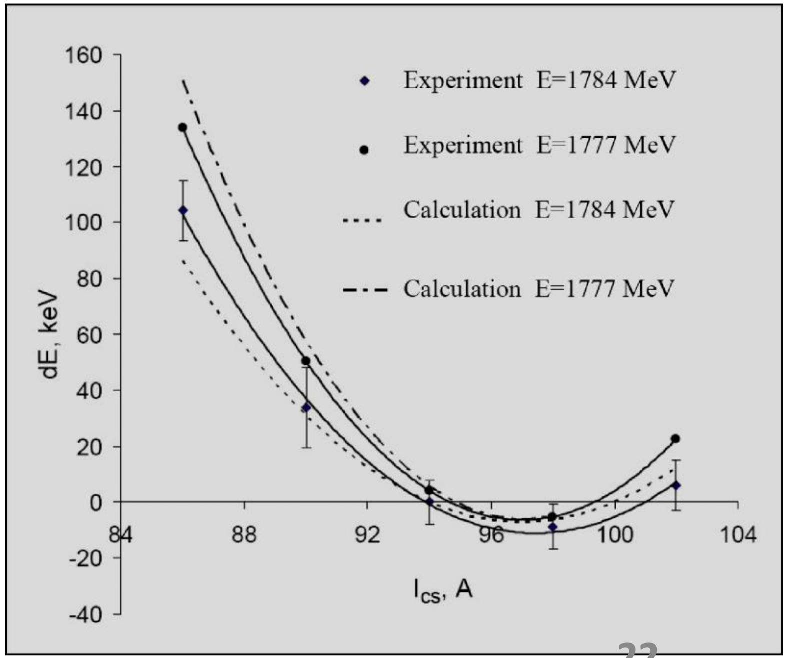
Spin tune shift measured at incorrect compensation of KEDR detector field:



Minimization by adjusting field of anti-solenoids:

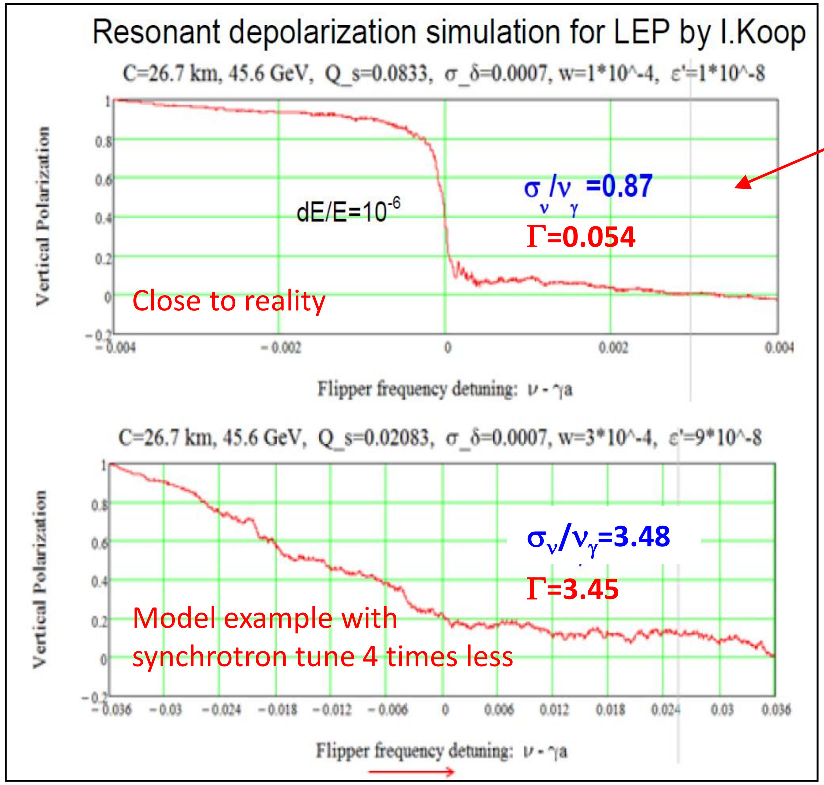
betatron coupling (~1% in AS current);

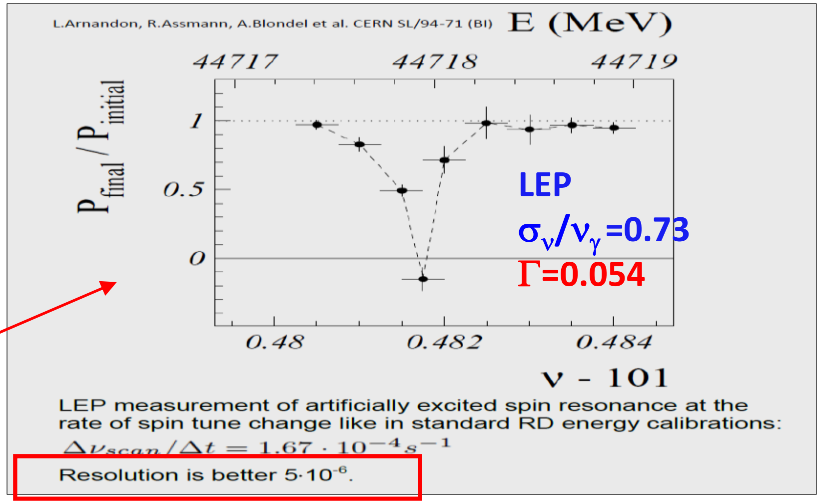
systematic error with RD in absolute energy (down to ~1 keV)



Issue of large modulation index in RD technique

Numerical simulation of RD process by I. Koop:
at large modulation index $\kappa = \frac{\textit{spin tune spread}}{\textit{synchrotron tune}} = \frac{\sigma_\nu}{\nu_\gamma} \geq 1$,
RD jump is not rigid (becomes "long-drawn"), accuracy may drop!





Another point of view: quantitative criterion rather, the increment in the spin precession phase for period of synchrotron oscillations due to radiative diffusion

$$\Gamma = \frac{11}{18}\frac{\nu^2}{\nu_\gamma^3 \tau_p f_0} \ll 1 \quad \text{for good RD resolution}$$

(τ_p is S-T polarization time). Γ characterizes the broadening of the spin resonance line width.

S.Nikitin, Talk at IAS Program on HEP, Jan. 2018

Collider	E, GeV	σ_ν	ν_γ	τ_p , min	f_0 , kHz	σ_ν/ν_γ	Γ	Resolution
VEPP-4M	1.85 4.73	0.0015 0.0098	~0.01 ~0.01	4200 45	820	0.15 ≥1	5e-5 ~0.01	1e-9 ?
LEP	45.6	0.061	0.083	300	11	0.73	0.054	5e-6
FCCee	45.6 80	0.039 0.119	0.025 0.051	15000 900	3	1.56 2.35	0.155 0.708	? ?
CEPC	45.6 80	0.039 0.120	0.028 0.04	15900 957	3	1.39 3.0	0.104 1.84	? ?

The parameter of spin phase diffusion $\Gamma \propto (\sigma_\nu/\nu_\gamma)^2/\nu_\gamma \propto \frac{1}{\nu_\gamma^3}$ is more sensitive to synchrotron tune than the modulation index.

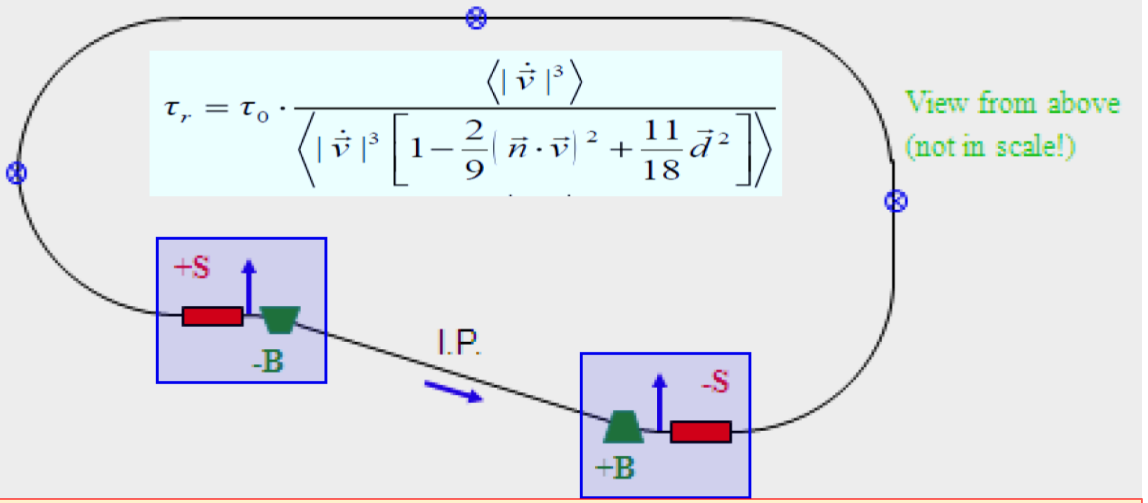
Synchrotron tune needs to be increased for providing better resolution of RD technique! In principle, a study with $\sigma_\nu/\nu_\gamma \geq 1$ is possible at VEPP-4M, where we have recently started RD experiments at the Upsilon energy.

Longitudinal polarization with minimization of spin-orbit coupling

One of LP options for SuperB

Different-in-sign 90[0] solenoids and anti-symmetric bend in between.

I.Koop . FACTORIES '08. 14-16 Apr. 2008,



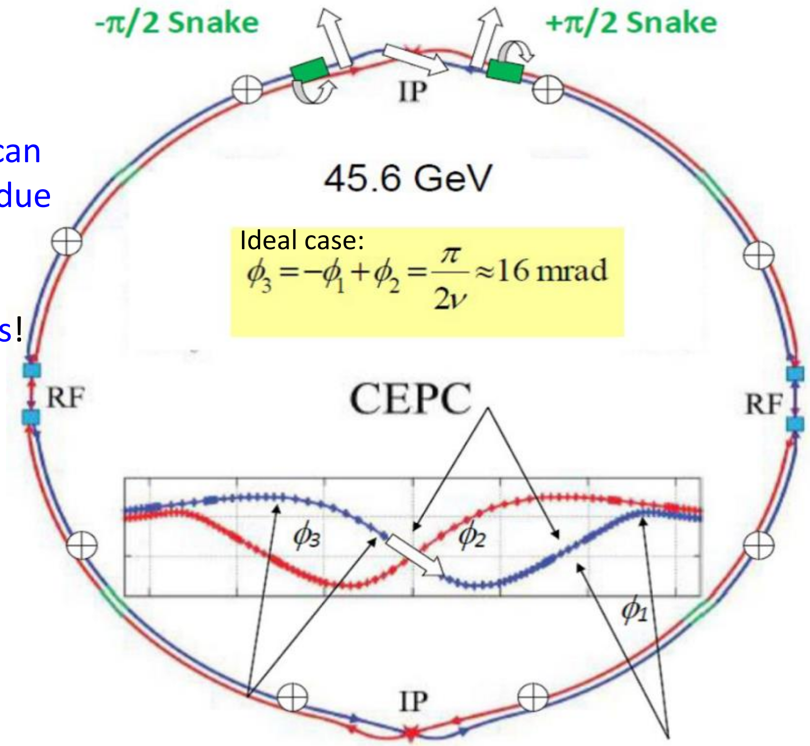
$$\tau_r = \tau_0 \cdot \frac{\langle |\dot{\vec{v}}|^3 \rangle}{\left\langle |\dot{\vec{v}}|^3 \left[1 - \frac{2}{9} (\vec{n} \cdot \vec{v})^2 + \frac{11}{18} \vec{d}^{\,2} \right] \right\rangle}$$

n direction is achromatic in arcs: $\mathbf{d}_{arc} = \gamma dn/d\gamma + \mathbf{d}_{beta} \approx \gamma dn/d\gamma = 0$

Antisymmetric rotator insert system: solenoids $S_\pm$ rotate spin by $\pm\pi/2$
Bends $B_\pm = \pm\pi/2\nu$ rotate by $\pm\pi/2$ (bends to left and to right of IP)).
Contributions to spin chromaticity from left and right parts of rotator system cancel each other. Thus, depolarization effect of SR in arcs is mainly suppressed (only not so large contribution from excited betatron oscillations is retained)
S-shaped form of orbit in CEPC/FCCee helps to do it at Z-peak!

CEPC-Z case can be analogue due to successful combination of parameters!

e.g. $H_{||}L \approx 8T \times 30$ m solenoid-based snake



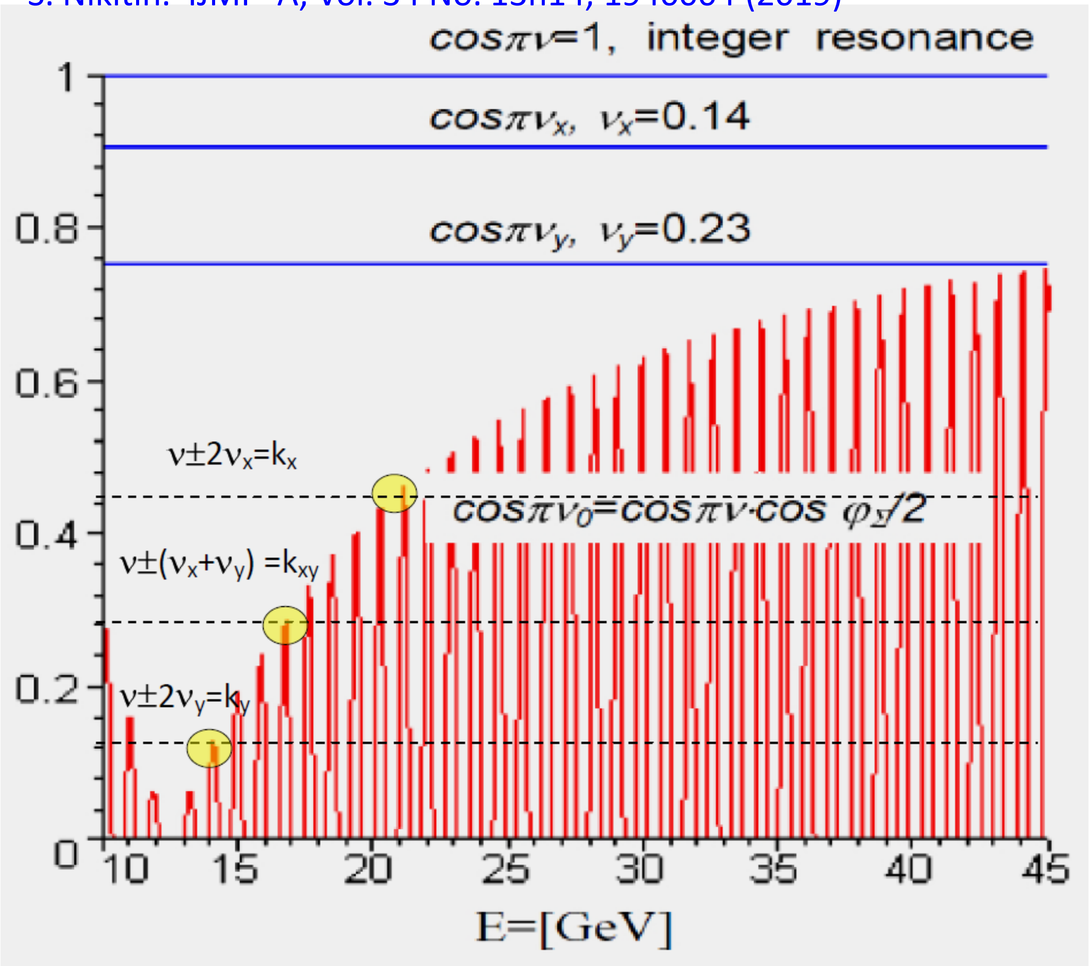
Wagging orbit in the CEPC interaction region with bending angles close to optimal ones (**half crossing angle=15 mrad**) allows us to consider respective spin kinematic design basing on solenoid inserts
S.Nikitin, Talk at IAS Program on HEP, Jan. 2018, Hong Kong;
IJMP A, Vol. 34 No. 13n14, 1940004 (2019)

Radiative relaxation time τ_r of polarization in order of magnitude can be comparable with S-T time τ_p=260 hrs and much larger than luminosity beam life time. In top-on mode, time-average degree of longitudinal polarization will be closed to polarization degree of beam injected from booster!

Scheme to avoid all main spin resonances in CEPC booster

to issue on how to accelerate polarized beam in booster

S. Nikitin. IJMP A, Vol. 34 No. 13n14, 1940004 (2019)



Combined Partial Siberian Snake of two helix snakes + solenoid with field=const

$$\varphi_\Sigma(E) = \varphi_s \cdot \frac{10}{E} + \varphi_h \,,$$ angle of combined rotation around velocity

$\varphi_s = const \approx 0.93\pi$ rad, rotation in 97 T·m solenoid at 10 GeV

$\varphi_h = 0.8$ rad, rotation in system of two helix snakes

Parameters of helix snake in system of two consecutive such ones

φ rad	H Tesla	L m	M number of turns	E GeV	X_{max} mm	Y_{max} mm	R radiation loss factor
0.4	0.89	8.6	4	10	5	3.7	6.2
				45.6	1.1	0.8	0.3

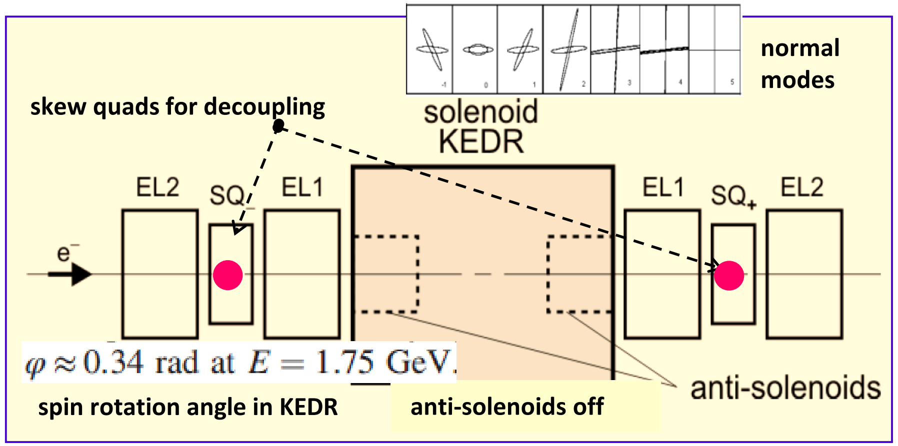
At marked points ○, the rate of crossing the spin-betatron resonances related to quadratic nonlinearities drops sharply. Here, apparently, one needs to apply a method of fast jump in betatron tunes .

Crossing integer spin resonance using Partial Siberian snake at VEPP-4M

A.K. Barladyan et al., DOI:10.1103/PRAB 22.112604

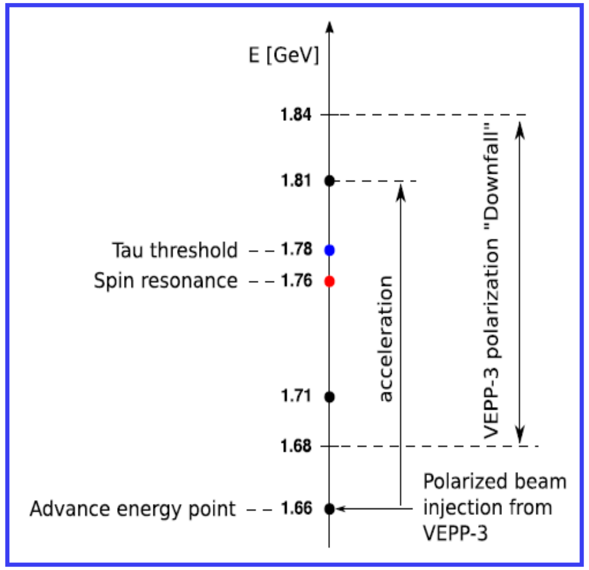
Why study crossing spin resonances?

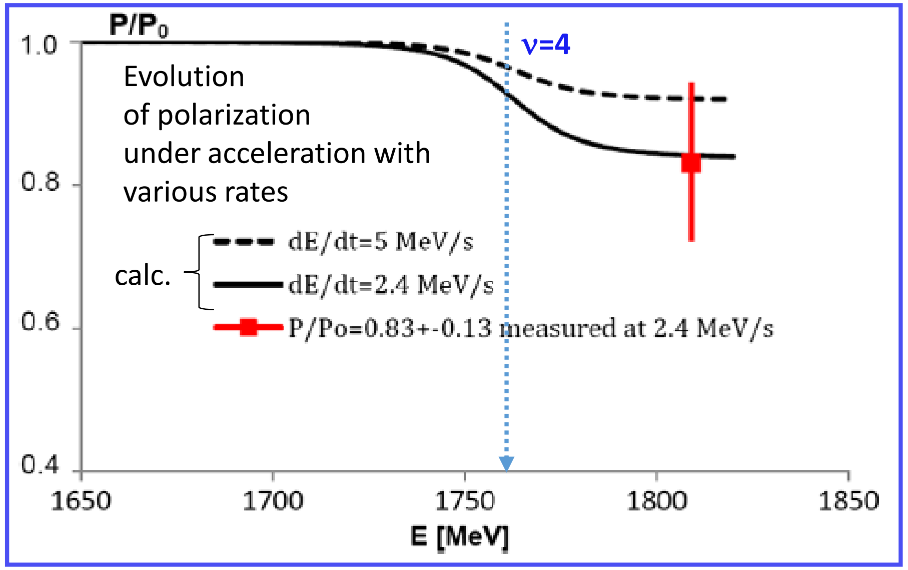
- Alternative way to obtain polarization in future circular lepton colliders – via acceleration of polarized beams in booster
- Unique way leading to possibility of obtaining longitudinal polarization
- Unlike proton machines, this technique in e+e- rings has been much lesser studied (specificity is complication associated with depolarization due to synchrotron radiation)



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-ν_y 12-ν_x	13 13	50
1948 1965 2001 2018	13-ν_y 12-ν_x ν_x-3 ν_y-4	13 13 21 21	100



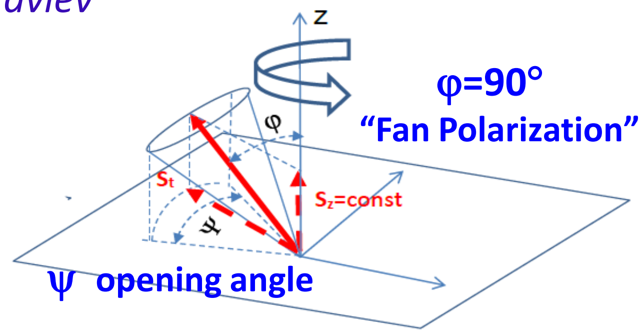


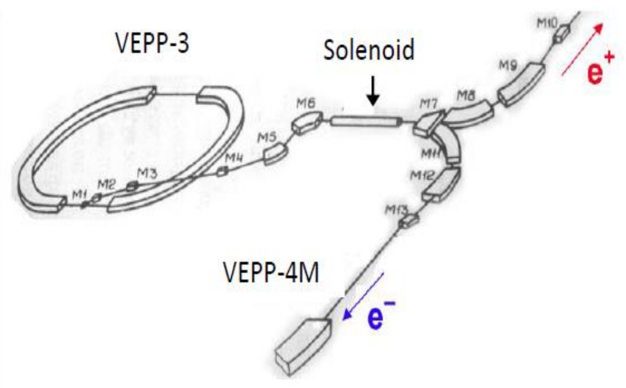
We have successfully performed an experiment on the adiabatic crossing of an integer spin resonance, using the longitudinal field of the KEDR detector as a partial Siberian snake (with the anti-solenoids turned off).

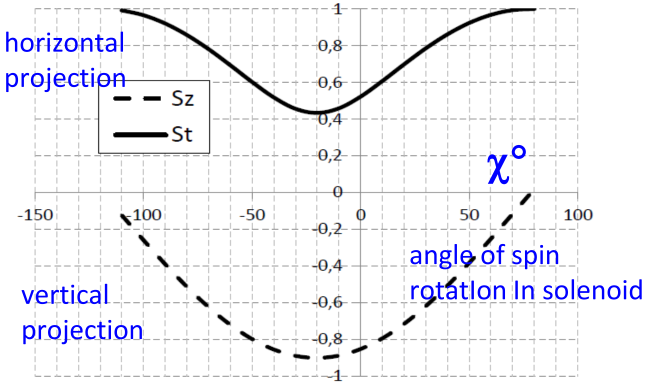
"Pulsar" - Fan Polarization test at VEPP-4M (2015)

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

Concept by **I.Koop** for FCCee beam energy measurement at injection (HF2014): 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 and detecting scattered electrons instead of CBS gamma- quanta.



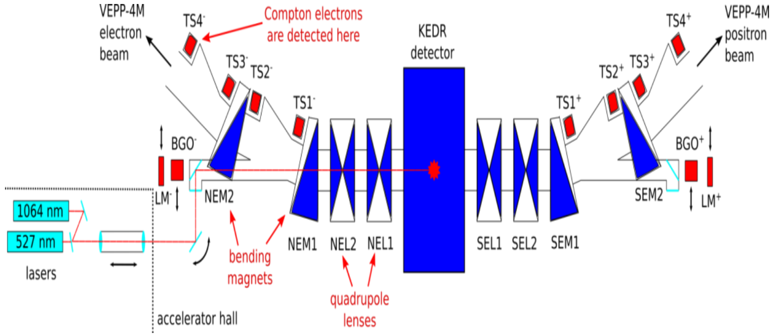


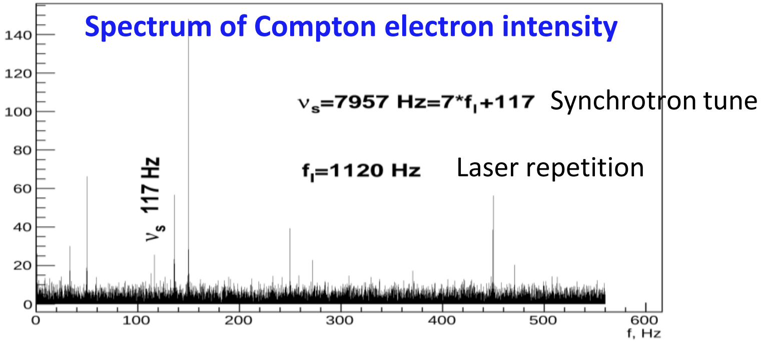


Compton electron counting rate 1-2 kHz
Measurement time 130 s
Normalization by laser power
Discrete Fourier analysis:

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

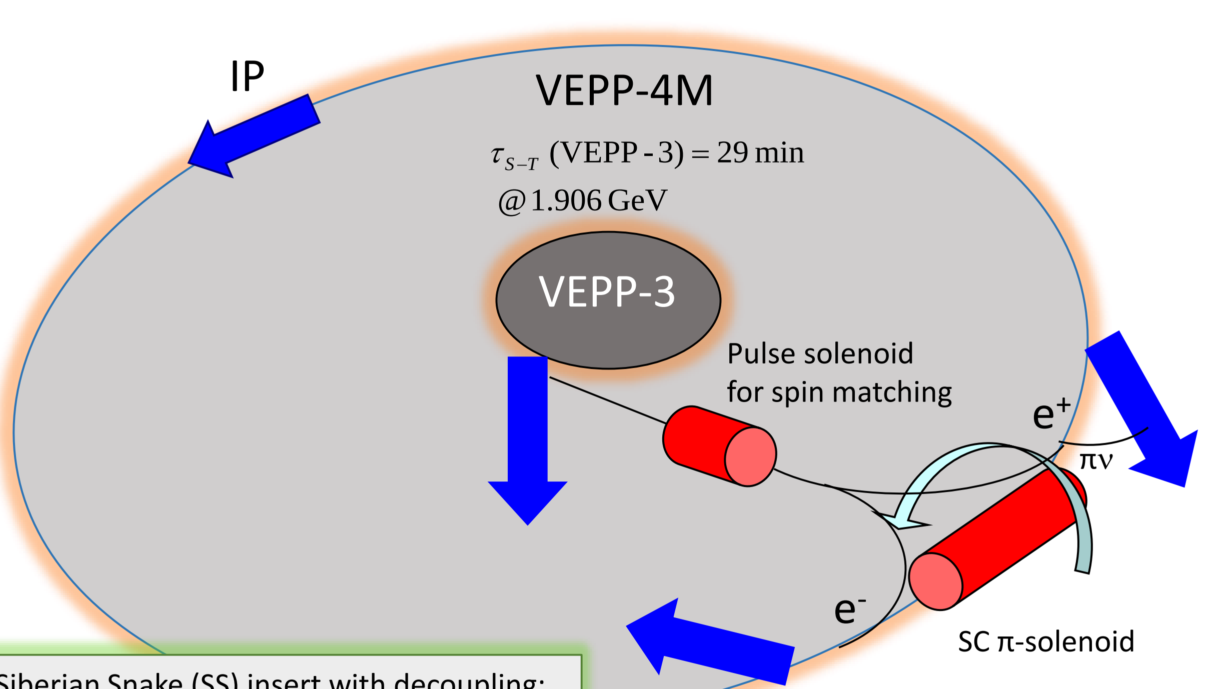
No spin precession frequency in spectrum was observed!





We intend to repeat the experiment by significantly reducing <H''>, a zero harmonic of the quadratic nonlinearity of the VEPP-4M field. According to preliminary analysis, it is the reason for the rapid diffusion of the fan opening angle.

Siberian Snake at VEPP-4M - back to old 1981 proposal



Siberian Snake (SS) insert with decoupling:
Two 145 cm × 71.7 kG solenoids (1.98 GeV)
Five 20 cm×(up to 3 kG/cm) quads
(1 normal +4 skew)
Insert length=532 cm
(in the project for VEPP-4)

Depolarization time with SS:

$$\tau_d \approx \frac{54}{11} \cdot \frac{\tau_{S-T}}{\pi^2 \nu^2} \cdot B(\nu, \nu_x) \propto E^{-7}$$

$\nu = \gamma a$

$B(\nu, \nu_x)$ – betatron factor

VEPP-4M Sokolov-Ternov time:

$$\tau_{S-T}[h]\Big|^{\text{VEPP-4M}} = \frac{1540}{E^5[GeV]}$$

70 hours at 1.85 GeV

Estimate with $B(\nu, \nu_x)$

(no optimization):

$\tau_d = 160$ min at $E = 1777$ MeV

$\tau_d = 120$ min at $E = 1846$ MeV

$\tau_d = 425$ min at $E = 1548$ MeV

Polarization life time after injection

S.A. Nikitin, E.L. Saldin, Preprint INP 81-19, 1981

Now, the project "Siberian snake" at VEPP-4M is under consideration in the form close to that which was proposed in 1981 for VEPP-4. The implementation of the project would make it possible to investigate the features of the radiative kinetics of longitudinal polarization (LP) with the Siberian Snake. They have not yet been sufficiently studied experimentally. This is important since three Siberian Snakes are supposed to be used in the BINP Super C-Tau factory project.

Thanks for attention!