Resonant Depolarization at VEPP-4M and FCC-ee

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EARLY MILESTONES

1963 Sokolov and Ternov (USSR) discovered in theory radiative self-polarization of relativistic electrons and positrons in magnetic field

1963 Discovery of Touschek effect (IBS-based) from dependence of beam lifetime on beam current at AdA storage ring (exported from Frascati, INFN, Italy) in Orsay (France)

1967 Baier and Khoze (INP, Novosibirsk) considered spin dependence of IBS rate

1968 Proposals to use registration of Touschek electrons for polarization measurement and resonant depolarization for energy measurement (VEPP-2 Team, INP)

1969 Baier and Khoze, paper on determination of transverse polarization in storage rings; Derbenev, Kondratenko and Skrinsky (DKS), beginning of theoretical series on spin dynamics

1970 VEPP-2 Team observed beam polarization at 625 MeV using Touschek electron counters and applied resonant depolarization on *external* spin resonance. One year later, those results were described in INP theoretical paper by Baier

1972 Beam polarization was observed by resonant depolarization on *machine* spin resonance at 536 MeV ACO (Orsay)

1975 First RD application for precise measurement of particle mass (ϕ-meson) at VEPP-2M

WHERE RD WAS USED TO MEASURE MASS

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)

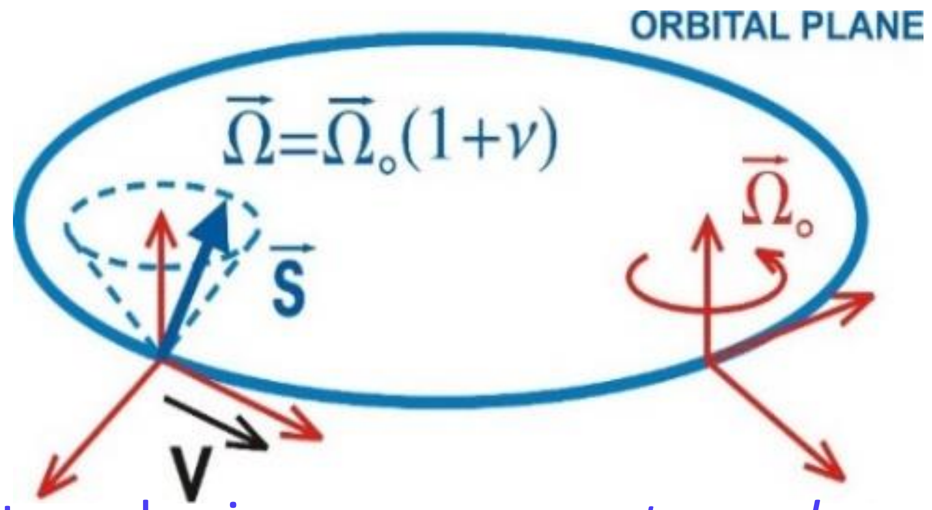
Z (ALEPH etc., LEP, 1991)

J/ψ, ψ', $\psi(3770)$ (KEDR, VEPP-4M, 2002-2008)

τ (KEDR, VEPP-4M, 2005-2008)

STORAGE RING WITH PERFECTLY FLAT ORBIT

$\nu = \gamma\left(\frac{g-2}{2}\right) = \gamma a$, spin tune parameter
$\omega = \langle\Omega\rangle = 2\pi f_0(1+\nu)$, average spin frequency
$\omega_0 = \langle\Omega_0\rangle = 2\pi f_0$, average revolution frequency



Ω, spin precession frequency
Ω_0, Larmor frequency

Obtain polarized beam. Create external spin resonance $\omega \pm \omega_d = k\omega_0$. Scan ω_d external field frequency, detect depolarization, determine ratio ω/ω_0 and then beam particle energy from

$$\langle E\rangle = \frac{eR}{2\,\pi}\oint B_\perp(\theta)d\theta = \left(\frac{\omega}{\omega_0} - 1\right)\left(\frac{g-2}{2}\right)^{-1} mc^2 = \nu \cdot 440.648\,4587(27)\ \text{MeV}$$

$\left(\frac{g-2}{2}\right) = 1.159\,652\,180\,91 \times 10^{-3} \pm 2.6 \times 10^{-13}$; $mc^2 = (0.510\,998\,9461 \pm 3.1 \times 10^{-9})$ MeV

In accordance with the accuracy in the fundamental constant values,
the limiting relative accuracy of RD is 6.1×10^{-9}.
In units of electron mass this accuracy is an order of magnitude more higher.

RD-BASED MASS MEASUREMENT ACCURACY QUESTIONS

Groups of error sources

- mean energy value determination basing on measured spin frequency
- energy stability in time domains between energy calibrations
- determination of Center-of-Mass energy by mean beam energy

Possible sources

Radial orbit distortions:

non-stability of currents in magnet coils, temperature variations, geomagnetic variations, tidal perturbations…

Vertical orbit bumps at sections without bend magnets

Violation of simple energy-spin tune relation (non-flat orbit with torsions):

random perturbations of vertical orbit, weak longitudinal magnetic fields, vertical orbit bumps at sections with bend magnets (see the complete BMT-Thomas equation!)

Azimuthal dependence of energy due to radiation losses

Inclination of RF cavity axis to beam axis

Effects of beam parameters in IP:

momentum and angular spreads in beam, crossing angle, inaccurate colliding beam convergence, parasitic vertical dispersion, FF chromaticity, beam potential, Beamstrahlung…)

…

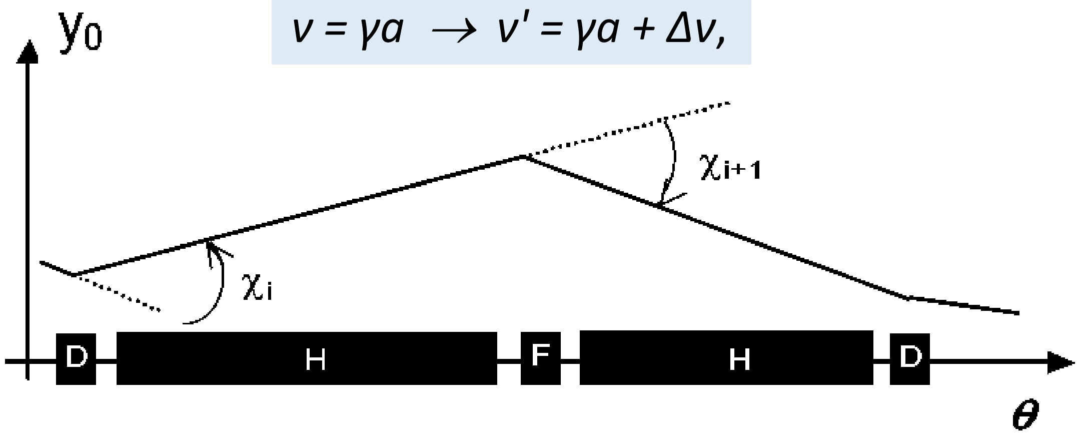
The most important of these issues have been studied in relation to the measurement of masses on LEP and VEPP-4M. Similar work ongoing for FCC-ee and CEPC projects

(All about this in Talk by A. Bogomyagkov , 27/09)

example: SPIN TUNE SHIFT DUE TO VERTICAL ORBIT DISTORTIONS

This issue was first under consideration at LEP: *L. Arnaudon et al. CERN SL/94-71 (BI)*

$\nu = \gamma a \;\rightarrow\; \nu' = \gamma a + \Delta\nu,$



Spin tune shift :

$$\Delta\nu \approx \frac{\nu^2}{8\pi \sin\pi\nu}\left[\cos\pi\nu \sum_i \chi_i^2 + \sum_i \sum_{j\neq i} \chi_i \chi_j \cos(\pi\nu - |\Phi_{ij}|)\right], \quad \Phi_{ij} = \nu \int_{\theta_i}^{\theta_j} K d\theta$$

In smooth approximation

$$\overline{\Delta\nu} = \frac{\nu^2}{2} \cdot \frac{\langle y_0^2 \rangle}{R^2 Q} \sum_{k=-\infty}^{\infty} \frac{k^4}{(\nu - k)(\nu_y^2 - k^2)^2}, \text{ systematic shift}$$

$$\sigma_{\Delta\nu} = \sqrt{\overline{(\Delta\nu)^2} - (\overline{\Delta\nu})^2} = \frac{\nu^2\sqrt{3}}{2} \cdot \frac{\langle y_0^2 \rangle}{R^2 Q} \sqrt{2\nu \sum_{k=-\infty}^{\infty} \frac{k^8}{(\nu_y^2 - k^2)^2 (\nu - k)^2 (\nu + k)}}, \text{ dispersion}$$

$$Q = \frac{\pi}{2\nu_y^3} \cot\pi\nu_y + \frac{\pi^2}{2\nu_y^2} \csc^2 \pi\nu_y$$

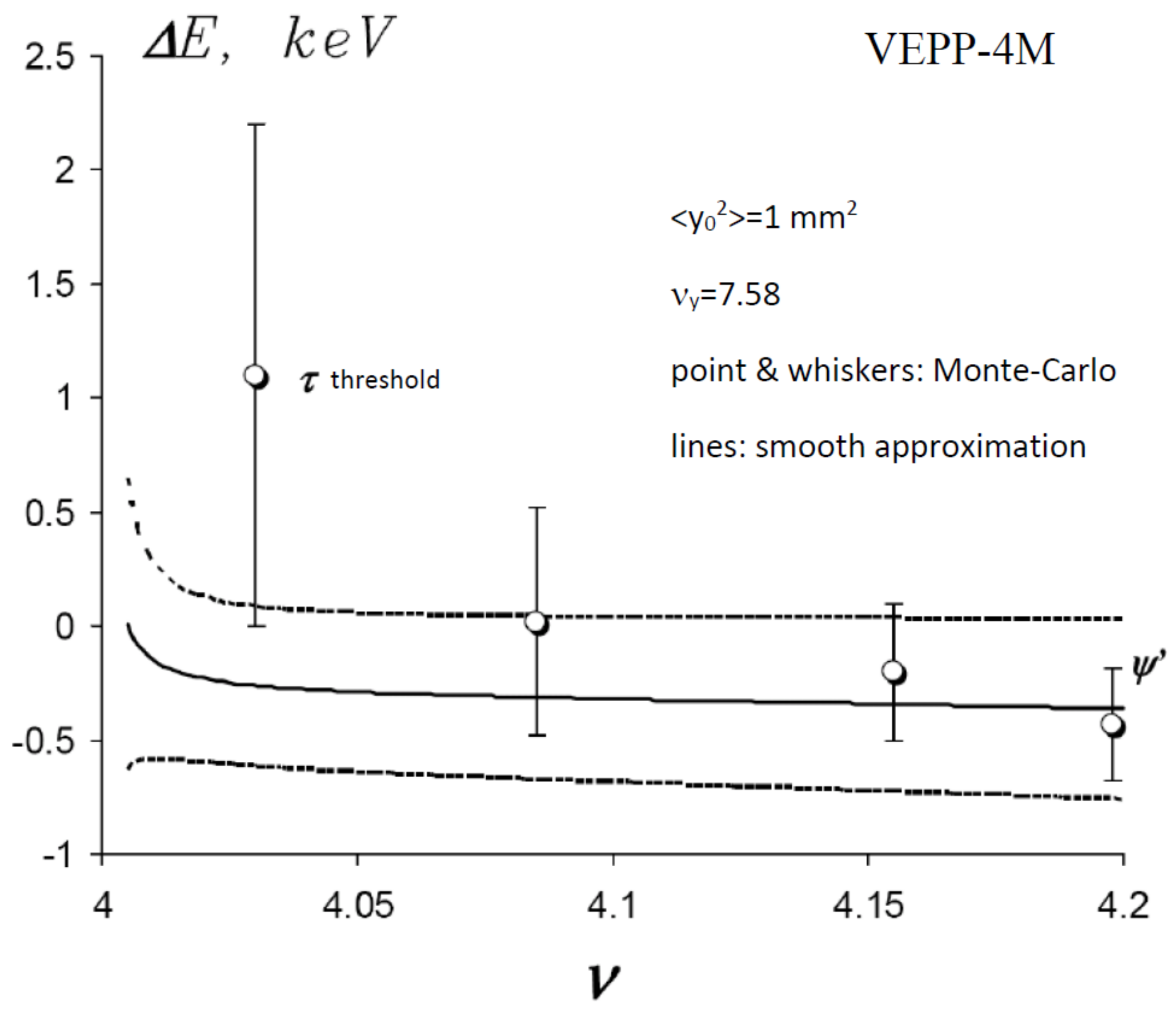
A.V. Bogomyagkov, S.A. Nikitin, A.G. Shamov.
RUPAC 2006 Proc., http://arxiv.org/abs/1801.01227

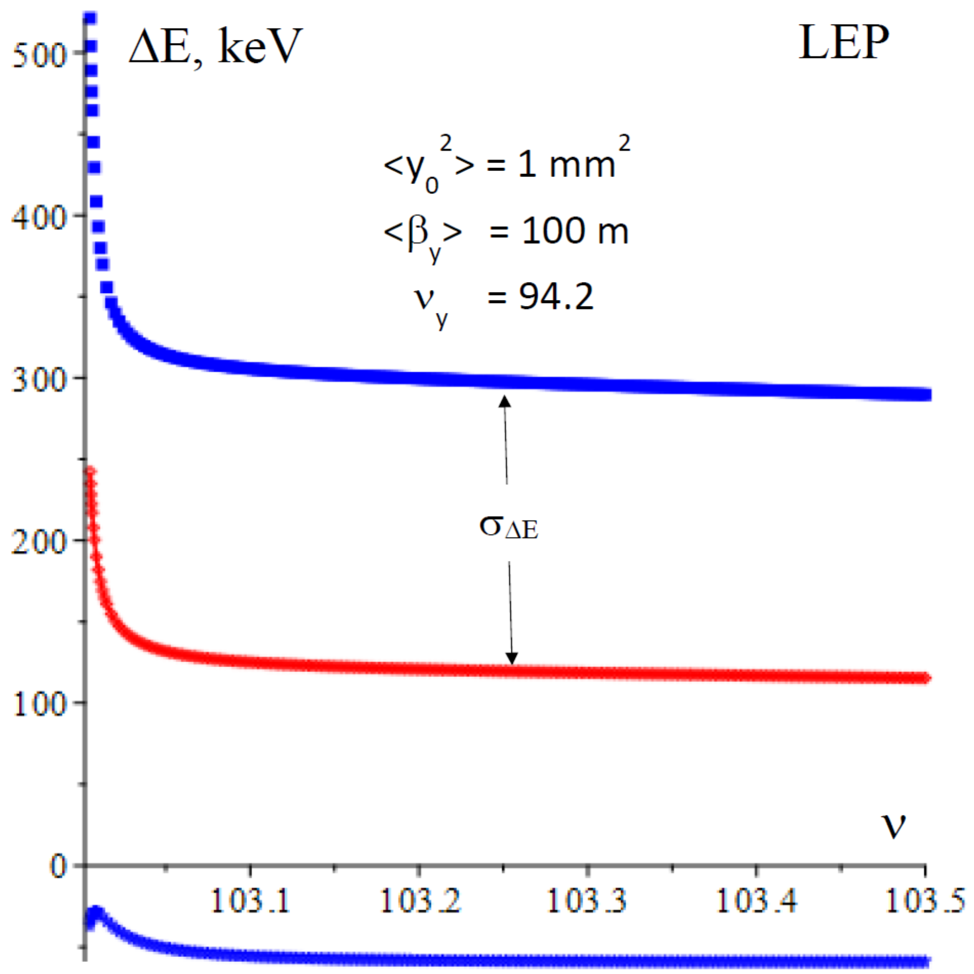
E=45.6 GeV

	FCC-ee	CEPC	LEP
ν_y	267.22	365.22	94.2
$\sqrt{\langle y_0^2 \rangle}$, mm	1	1	1
$\Delta\nu/\nu$	-1.8e-6	-3.1e-6	~2.6e-6
$\sigma_{\Delta\nu}/\nu$	2.6e-6	4.5e-6	~3e-6

Correlation term $\chi_i \chi_j$ is drastically important!
This follows from the fact that the orbit is closed.
Otherwise, the result can change by orders of magnitude.
Dispersion of the spin tune shift ($\sigma_{\Delta\nu}$) is an error in absolute energy determination.
A closed orbit in supercolliders (FCC-ee, CEPC) will be corrected to << 1 mm. Therefore, a given source of error is expected to be suppressed.

SPIN TUNE SHIFTS DUE TO ORBIT VERTICAL DISTURBANCES AT VEPP-4M AND LEP

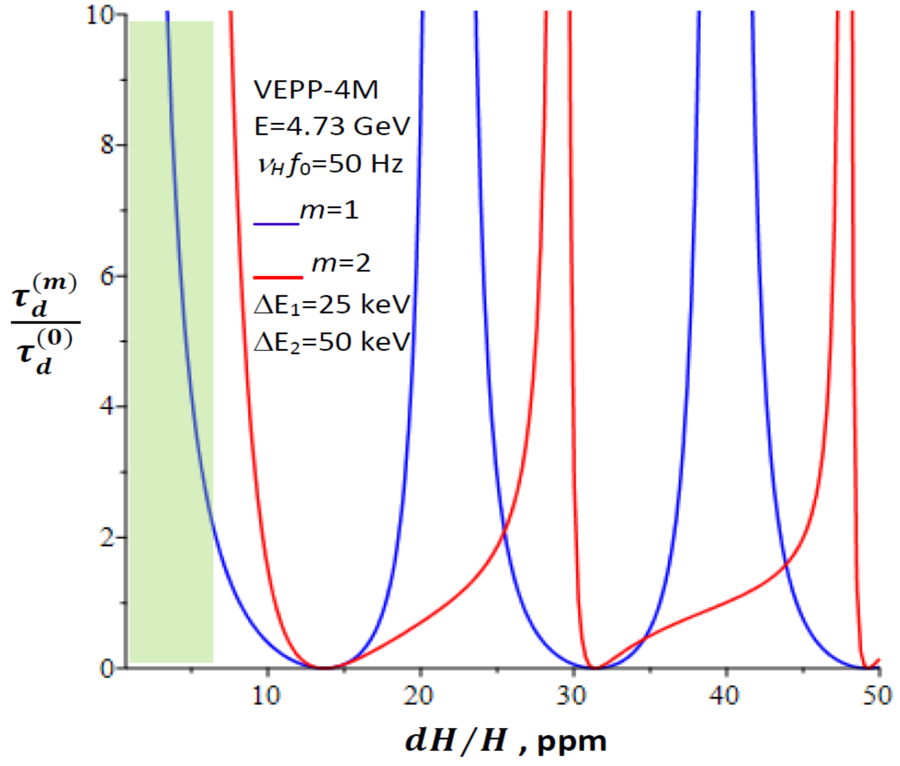


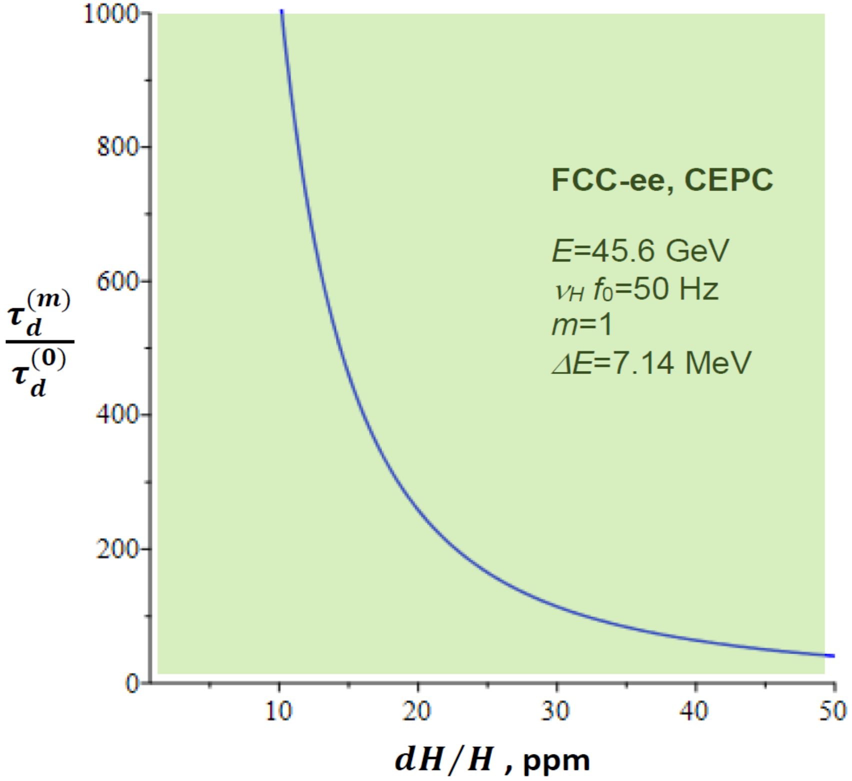


REGULAR FIELD PULSATIONS

Low frequency modulation resonances $\overline{\nu} + m \cdot \nu_H \pm \nu_d = k$ due to guide field regular ripples with an amplitude dH/H and a frequency $f_0 \nu_H$ can lead to systematic errors. This is possible if the ratio of the depolarization time at the *m*-th resonance to that time at the main resonance (*m*=0) is less than or close to unity:

$$\frac{\tau_d^{(m)}}{\tau_d^{(o)}} = \left[\frac{J_0(\Delta_H/\nu_H)}{J_m(\Delta_H/\nu_H)}\right]^2, \Delta_H = \nu \frac{dH}{H}$$





VEPP-4M: in **green** zone, parasitic RD events can be eliminated by minimizing the amplitude of the depolarizer

FCC-ee, CEPC: it seems no problem with influence of low frequency modulation spin resonances on RD

SYNCHROTRON OSCILLATIONS

- For a particle performing synchrotron oscillations with amplitude $\Delta\gamma$ and frequency ω_γ, the frequency of spin precession

modulation term

$$\frac{\omega}{\nu\omega_0} \approx \left[1 - \frac{\alpha}{2}\overline{\left(\frac{\Delta\gamma}{\gamma}\right)^2} + \alpha\frac{\Delta\gamma}{\gamma}\sin\omega_\gamma t\right]$$

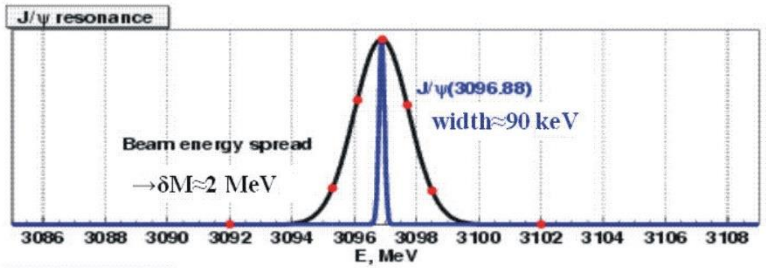
shift and broadening

- The term of a shift and broadening of a spin line determined through the momentum compaction factor α which is much less than the required RD accuracy of 10^{-6} ($2\sigma_\gamma^2 = \overline{(\Delta\gamma/\gamma)^2}$):

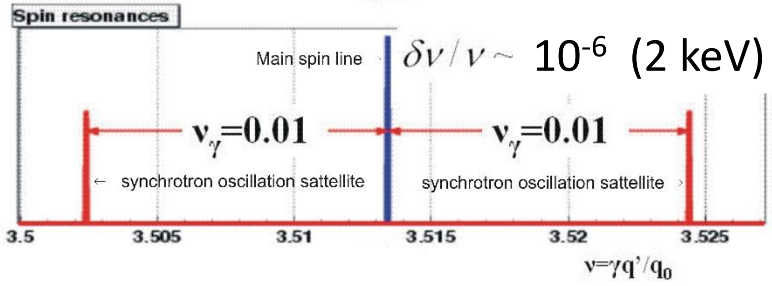
$$\frac{\Delta\omega}{\nu\omega_0} \approx \alpha\sigma\gamma^2 \sim \begin{cases} 10^{-9}, \mathrm{VEPP-4M}, \alpha = 0.017, & \sigma_\gamma \approx 3\cdot 10^{-4}, E = 1.8\ \mathrm{GeV} \\ 10^{-12}, \mathrm{FCC-ee}, \alpha = 14.8\cdot 10^{-6}, & \sigma_\gamma \approx 3.8\cdot 10^{-4}, E = 45.6\ \mathrm{GeV} \end{cases}$$

- Because of averaging over the phase of synchrotron oscillations the resulting error in determination of an average particle energy by RD technique is much less than the beam energy spread.
- Forced depolarization at a synchrotron modulation resonance of the *m*-th order occurs at the rate obtained by averaging over the ensemble of particles in the beam ($\sigma_\nu = \nu\sigma_\gamma, \nu_\gamma = \omega_\gamma/\omega_0$):

$$\frac{1}{\tau_d^{\{m\}}} = \frac{1}{\tau_d}\overline{J_m^2\left(\frac{\nu}{\nu_\gamma}\frac{\Delta\gamma}{\gamma}\right)} = \frac{1}{\tau_d} I_m\left(\frac{\sigma_\nu^2}{\nu_\gamma^2}\right)\exp\left(-\frac{\sigma_\nu^2}{\nu_\gamma^2}\right).$$



- The ratio of the rates of depolarization at the 1st modulation (m= 1) and the main resonance (m= 0): $\tau_d^{\{0\}}/\tau_d^{\{1\}} = I_1\left(\frac{\sigma_\nu^2}{\nu_\gamma^2}\right)\Big/ I_0\left(\frac{\sigma_\nu^2}{\nu_\gamma^2}\right) \approx 0.02$ at 1.85 GeV VEPP-4M . It is possible to register RD at the first sideband resonance if the nominal amplitude of the depolarizer field is exceeded by √50=7 times (a systematic error $\Delta\mathrm{E} = 4.4$ MeV)
- 45.6 GeV FCC-ee: $\tau_d^{\{0\}}/\tau_d^{\{1\}} \approx 0.26$, $\Delta\mathrm{E} \approx 11$ MeV. Side resonances easy to distingwish and eliminate



METHODS FOR CIRCULATING e-BEAM POLARIZATION MEASEREMENT

- Polarimeter based on Intra-Beam Scattering (IBS)

  VEPP-2, ACO, VEPP-2M, VEPP-4, VEPP-4M … efficiency decreases sharply with increasing beam energy

- Compton-based polarimeters:

  Laser polarimeter

  SPEAR (1976), DESY, VEPP-4, LEP, HERA, VEPP-4M … efficiency increases with energy; good for **FCCee, CEPC**

  Scattering of SR by colliding beam

  VEPP-4 (1982) … applied in the detector MD-1 with transverse magnetic field of 1.1 T

- Spin Light-based polarimeter

  VEPP-4 (1983) … first observation of the spin dependence of SR intensity; was efficient for RD

- Møller polarimeter based on internal gaseous polarized target ($5 \cdot 10^{11}$ e^-/cm^2)

  VEPP-3 (2003) … polarized deuterium atoms from the "Deuteron" facility to study polarization in booster

LASER POLARIMETER

- Cross Section of Compton Scattering on relativistic electron beam with transverse polarization:

  $d\sigma = d\sigma_0 + d\sigma_1 \cdot \zeta_{ph}\zeta_e \cdot \sin\varphi,$

  ζ_{ph} is an extent of circular polarization of photons,

  ζ_e is an extent of transverse beam polarization,

  φ is an angle between a scattering plane and a plane perpendicular to electron polarization.

- Vertical asymmetry $A = d\sigma/d\sigma_0 = f(\lambda,\chi) \rightarrow$ 0.3 in extremum at $\underline{\lambda = \gamma\vartheta} \approx 1$ and $\chi = 2\gamma\hbar\omega/m \approx 1$,

  $\vartheta \ll 1$ is a scattering angle;

  γ is a relativistic factor;

  ω is an angular frequency of incident photons.

- Higher energy to advantage

  $\chi \approx 0.1$ at 5 GeV VEPP-4M; $\chi \approx 1$ at 45 GeV LEP, FCC-ee and CEPC $\rightarrow$ due to the high analyzing power, a high degree of beam polarization is not required

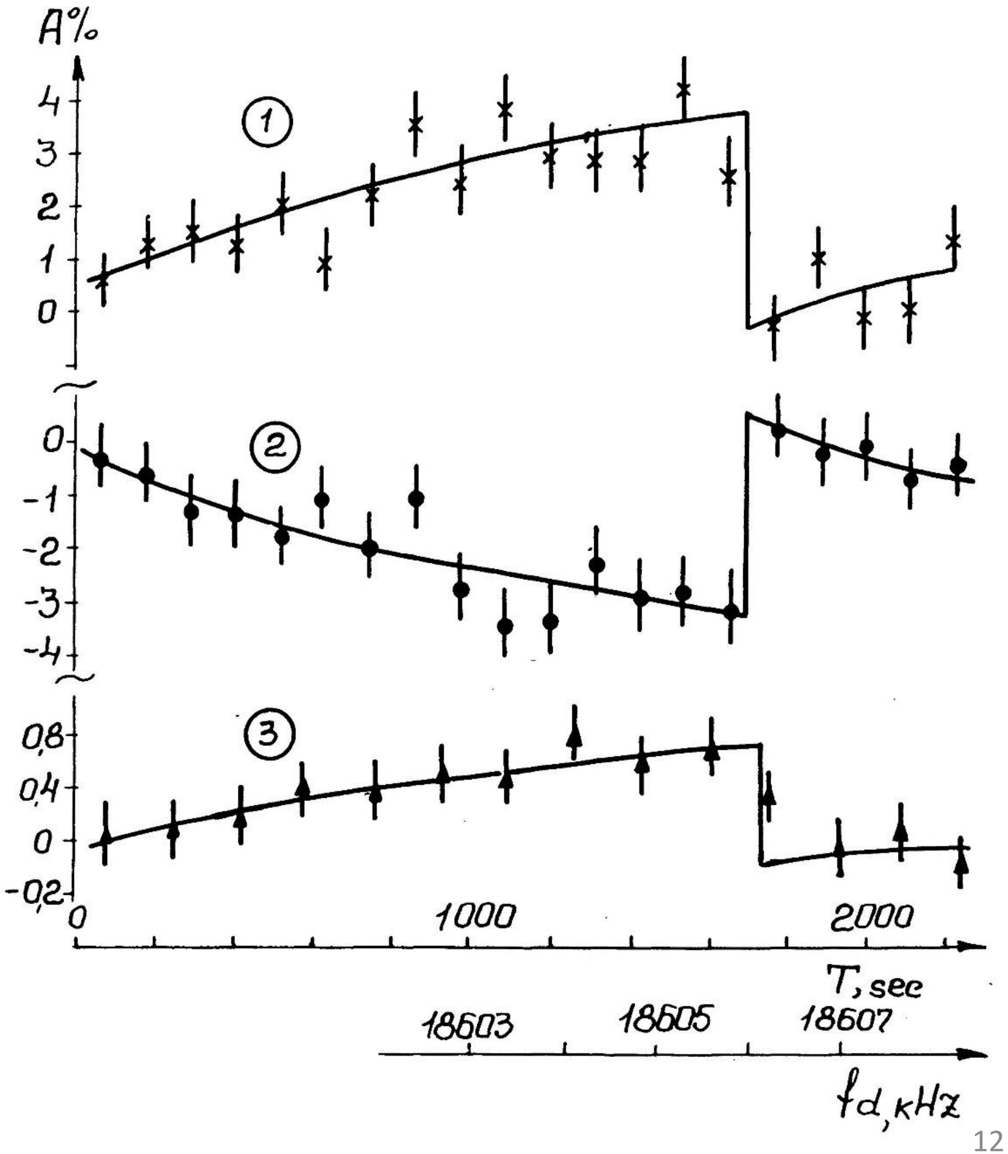
RD WITH COMPTON POLARIMETERS AT VEPP-4 (EARLY 80s)

$A = \frac{\text{up}-\text{down}}{\text{up}+\text{down}}$

E ≈ 5 GeV

1 and 2:
SR scattering on e$^-$ and e$^+$ beams,
120 um orbit separation in IP,
$\hbar\omega_c = 20$ keV,
registering quanta with 0.5÷5 GeV
$|A_1 - A_2| \sim 8\ \%$

3: laser light 532 nm
200÷900 MeV quanta were detected
$A_3 \lesssim 1\ \%$



POLARIMETER BASED ON INTRA-BEAM SCATTERING

- CMS cross section for e⁻e⁻ scattering

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

- Counting rate of Touschek particles

$$\dot{N} = \frac{\sqrt{\pi}r_0^2\,c\,N_b^2}{\gamma^5 V_b\left(\sigma_p/E\right)^3}\cdot\left(I_1 + \varsigma^2 I_2\right)$$

$$I_1=I_1(\varepsilon_1,\varepsilon_2),\ I_2=I_2(\varepsilon_1,\varepsilon_2),\ \varepsilon_{1,2} = \left(\frac{\Delta p_{1,2}}{\gamma\sigma_p}\right)^2$$

$$\Delta p_1= \Delta p_1(\mathbf{A}),\ \Delta p_2= \Delta p_2(\mathbf{A}_\Gamma)$$

A is a distance between the orbit and the counter

$\mathbf{A}_\Gamma$ is a geometric aperture

- The polarization effect $\Delta = \varsigma^2\frac{I_2}{I_1}<0$

SPIN LIGHT AT VEPP-4

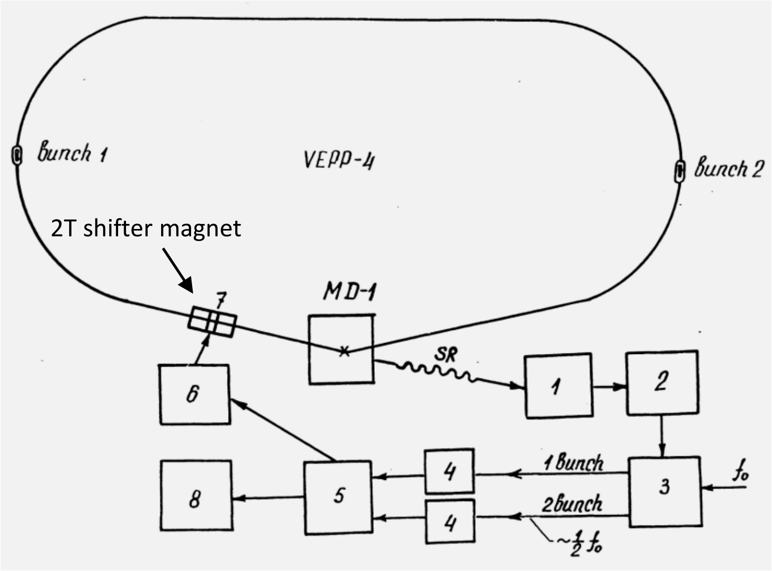
Interference between radiations of electric charge and of magnetic moment when particle moving along curved trajectory. SR power of a naturally polarized beam is larger than that of an un-polarized one by relative quantity:

$$\delta = \frac{\hbar\omega_c}{m\gamma}\zeta = \chi\zeta, \quad \omega_c = \frac{2}{3}\frac{eH}{m}\gamma^3.$$

The harder spectrum, the larger effect: $y = \frac{\omega}{\omega_c} >> 1, \quad \delta \approx y\chi\zeta$

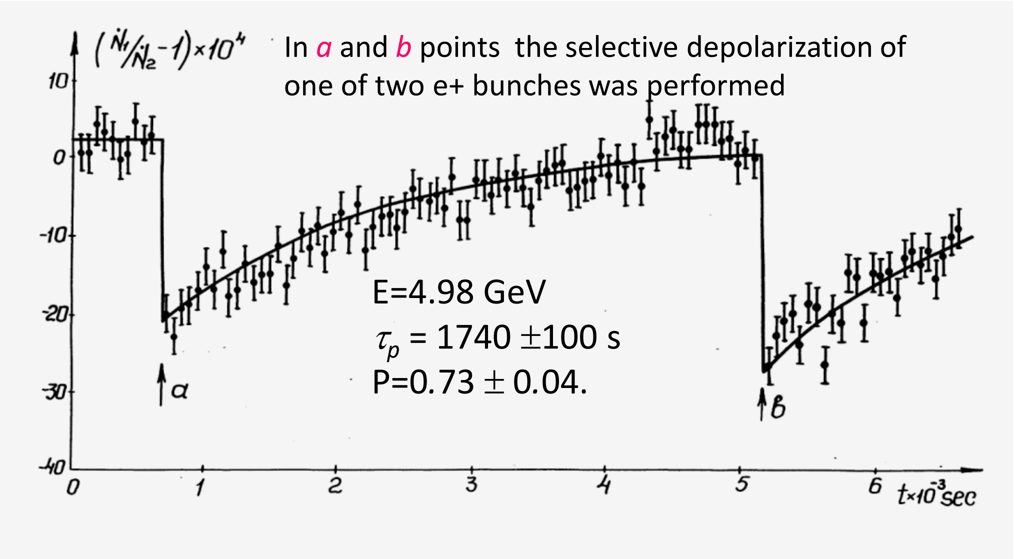
Sign of the effect changes at reversal of shifter magnet field

E=5 GeV, Hmax=2 T, y=7 (250 keV), $\delta \approx 5\cdot 10^{-5}$, comparison of polarized and un-polarized bunches, bunches were equalized as 10^{-4}; selective depolarization



1 - scintillation counter; 2 - discriminator; 3 - selector; 4 -counters; 5 -computer; 6 – “snake” power supply; “snake”; 8 - display.

S.A. Belomestnykh, A.E. Bondar, M.N. Egorychev, V.N. Zhilich, G.A.Kornyukhin, S.A. Nikitin, E.L. Saldin, A.N. Skrinsky, G.M. Tumaikin. Nucl. Instr. And Meth. A 227(1), (1983) 173-181.



Higher energy to advantage:

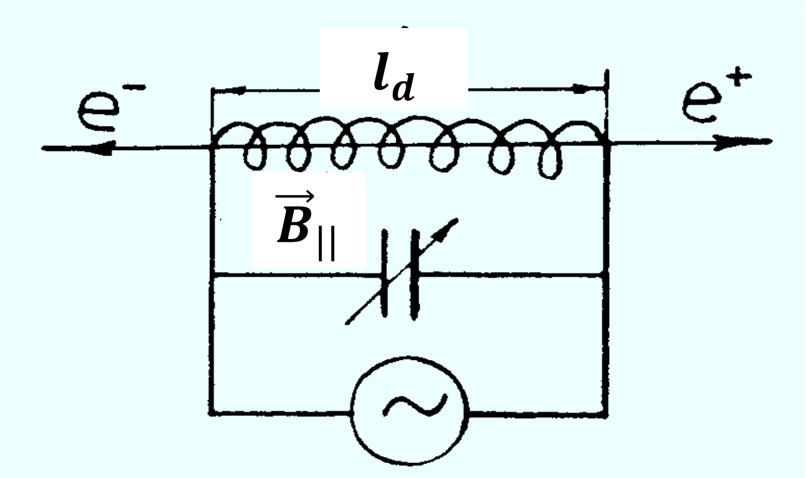
E=70 GeV, H_{max} =1 T, *y*=10 (30 MeV), $\delta \approx 10^{-3}$.

Disadvantages compared to a laser polarimeter:

- a magnet with a large field changes the optics
- a greater degree of polarization is required

DEPOLARIZER DEVICES

Solenoid



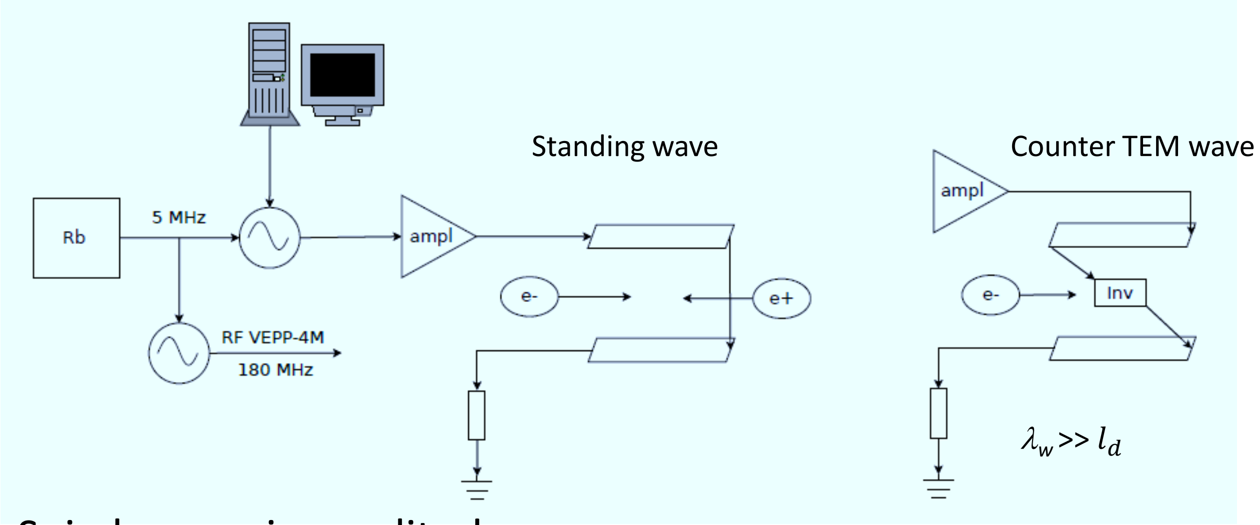
Spin harmonic amplitude

$$|w_k| = \frac{\hat{B}_{||} l_d}{2\pi B\rho}$$

$$|F^\nu| \equiv 1$$

Applied at low energies (VEPP-2M).

Strip line with matched load



Spin harmonic amplitude

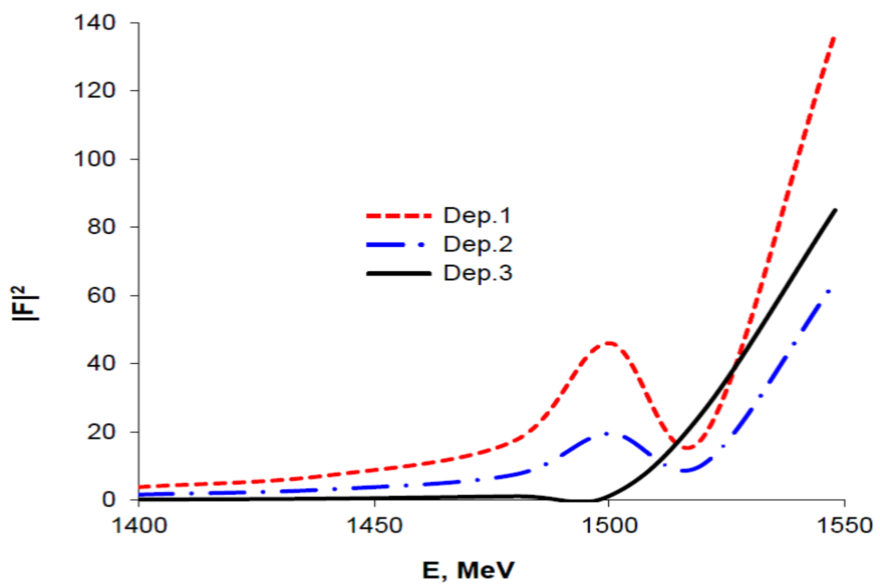
$$|w_k| = \frac{\nu \hat{B}_\perp l_d}{2\pi B\rho} |F^\nu|, \quad F^\nu = f(\theta, E, \nu_y) = f(\theta + 2\pi/N, E, \nu_y),$$

N is number of super-periods

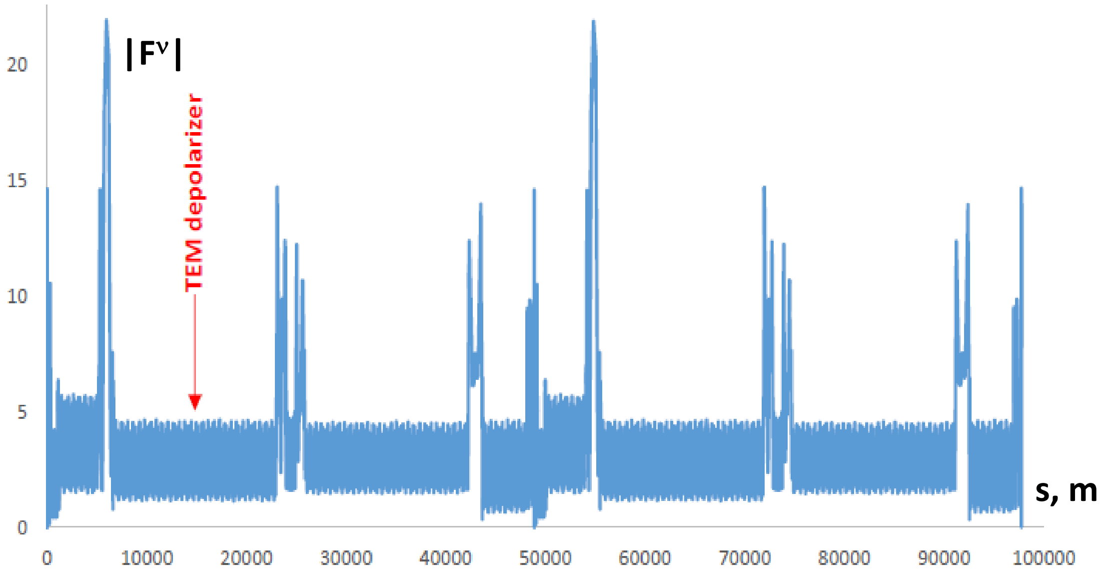
Due to the large values of $\boldsymbol{\nu}$ and the spin response factor $|\boldsymbol{F^\nu}|$ (**DKS, 1979**), it is beneficial at high energies. The factor $|\boldsymbol{F^\nu}|$, due to excited vertical oscillations, was measured for the first time in the VEPP-4 experiment to study resonant spin diffusion in the field of a counter TEM wave in the early 80s.

DEPENDENCE OF SPIN RESPONSE FACTOR ON AZIMUTH AND ENERGY

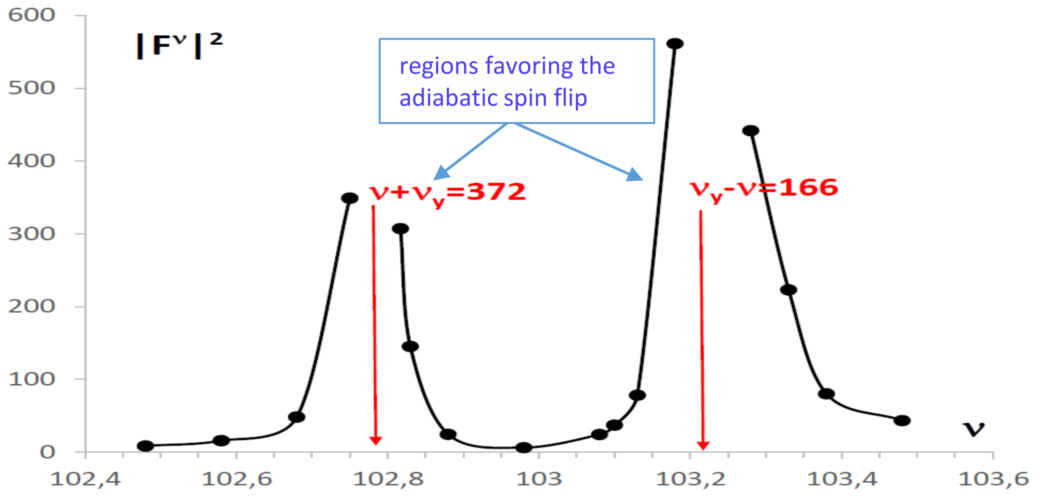
$|F^{\nu}|^2$ vs. energy for three depolarizers differing in locations at VEPP-4M



Spin response factor $|F^{\nu}|$ vs. azimuth at FCC-ee; E=45.6GeV (ν=103.48)



$|F^{\nu}|^2$ at the depolarizer location vs. energy in Z peak region (ν_y=269.215)



- In the experiment at VEPP-4M at E=1500 MeV , Dep. 3 was not able to depolarize beam, but Dep.1 did it in accordance with calculation.
- Forced depolarization rate is proportional to $|w_k|^2 \propto \nu^2|F^{\nu}|^2$. Factor $|F^{\nu}|^2$ grows in a vicinity of intrinsic resonances $\nu \pm \nu_y = k$. In this case, it is necessary to decrease the amplitude of the depolarizer in order to maintain optimal conditions for its use (with the aim to exclude depolarization at parasitic i.e. modulation resonances).
- At VEPP-4M we do not use the spin-flip mode (adiabatic crossing resonance) in energy calibration. In particular, this is not possible with the Touschek polarimeter (effect $\propto \zeta^2$). On LEP, the spin-flip was partially observed (with a laser polarimeter), which could indicate large amplitude values of the depolarizer harmonic $|w_k|$.

SCAN RATE AND SCAN SCALE

- The spectral linewidth of the VEPP-4M synthesizer is ~ 10^{-4} Hz. When scanning the depolarizer frequency with a selected constant rate df_d/dt the depolarizer linewidth δf_d is broadened and becomes

$$\delta f_d \sim \sqrt{df_d/dt}$$

- The ratio of the frequency scanning interval to the corresponding energy interval can be called the specific scan scale:

$$\varrho = \frac{\Delta f_d}{\Delta E} = \nu \frac{f_0}{E}.$$

- For the spin line width $f_0\,\delta\nu$ and energy accuracy ΔE, the following relations are preferable:

$$f_0\,\delta\nu \leq \delta f_d \leq \rho \Delta E$$

	Energy E GeV	Revolution freq. f_0 kHz	Specific scan scale $\varrho = \nu f_0/E$ Hz/keV	Energy accuracy ΔE keV	Scan scale $\varrho\Delta E$ Hz
VEPP-4M	1.85	820	1.9	1.85	1.9
LEP	45	11	0.025	100	2.5
FCC-ee, CEPC	45	3	0.007	100	0.7

With the same energy accuracy (~10^{-6}), the scan scale $\varrho\Delta E$ at very different colliders is approximately the same and close to 1 Hz!

CONDITIONS AT MONOTONE SCANNING

main mode in our RD practice

- The linewidths in the spectra of both the spin ($f_0\,\delta\nu$) and the depolarizer (δf_d) are approximately the same and meet the required energy accuracy ΔE :

$$f_0\,\delta\nu \leq \sqrt{\frac{df_d}{dt}} < f_0\nu\frac{\Delta E}{E} = \rho\Delta E$$

- Complete depolarization occurs in a time τ_d which doesn't exceed the time of polarization measurement at the point Δt_m , necessary for reliable detection of the depolarization jump ("jump between two measurement points")

$$\tau_d < \Delta t_m$$

- Conditions necessary for proper depolarization in the depolarizer noise-band:
  - "uncorrelated" successive crossings of a resonance (τ_p - Sokolov-Ternov time)
  - "rapidity" of the intersection in the spectrum band of the depolarizer

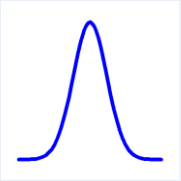
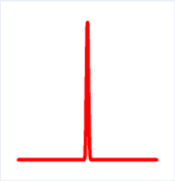
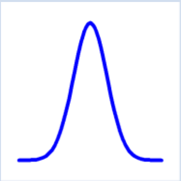
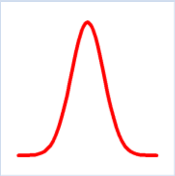
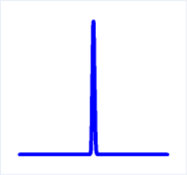
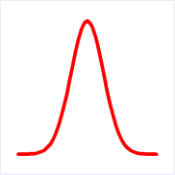
$$\nu^2 \geq \frac{\tau_p(\delta f_d)^3}{f_0^2}$$

$$(\delta f_d/f_0)^2 \gg |w_k|^2$$

- Corresponding depolarization time

$$\tau_d \approx \frac{\delta f_d}{4\pi|w_k|^2 f_0^2}$$

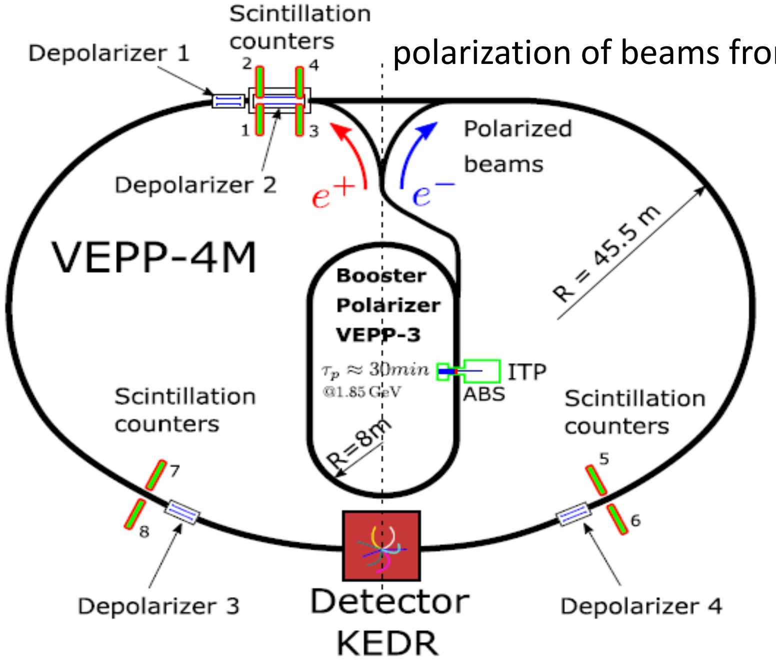
SCAN MODES AT VEPP-4M

Mode	Depolarizer harmonic amplitude $\lvert w_k \rvert$	Scan rate *keV/s*	Depolarizer line widening *keV*	Depolarization frequency resolution *keV*	Relative spectral linewidth	
					depolarizer	spin
"CLUB"	10^{-6}	10	2.1	~10		
"J/psi"	$5 \cdot 10^{-7}$	0.3	0.4	~2		
"CPT"	$4 \cdot 10^{-8}$	0.005	0.05	~0.002		

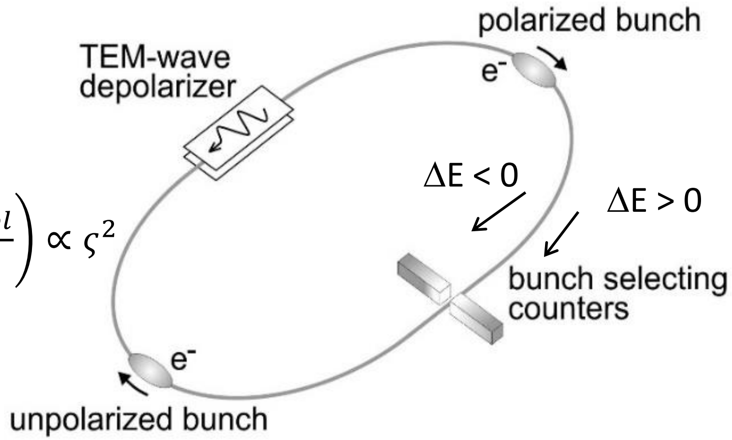
"Club": quick energy calibrations in regions of resonance substructure
"J/Psi": most precise calibrations in narrow resonance peaks
"CPT": precise comparison of spin frequencies of electron and positron

RD AT VEPP-4M WITH TOUSCHEK POLARIMETER

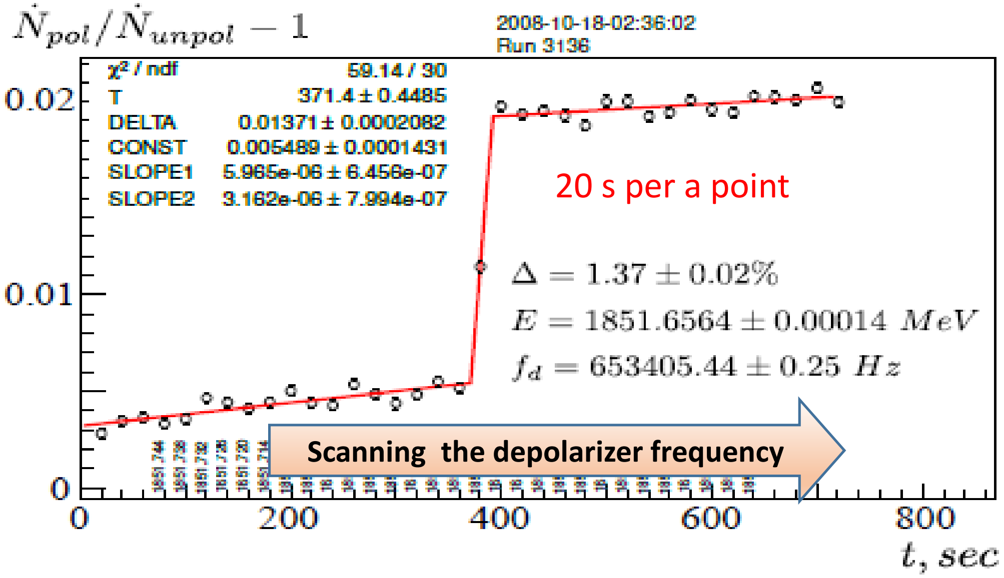
polarization of beams from VEPP-3 up to 80%



Two-bunch method

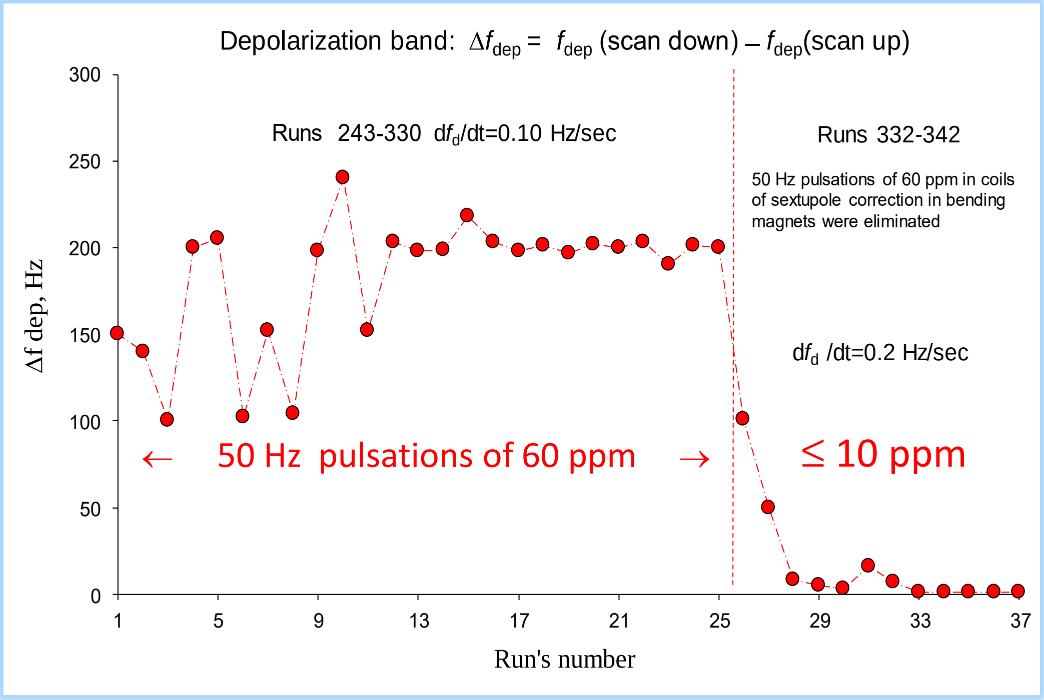


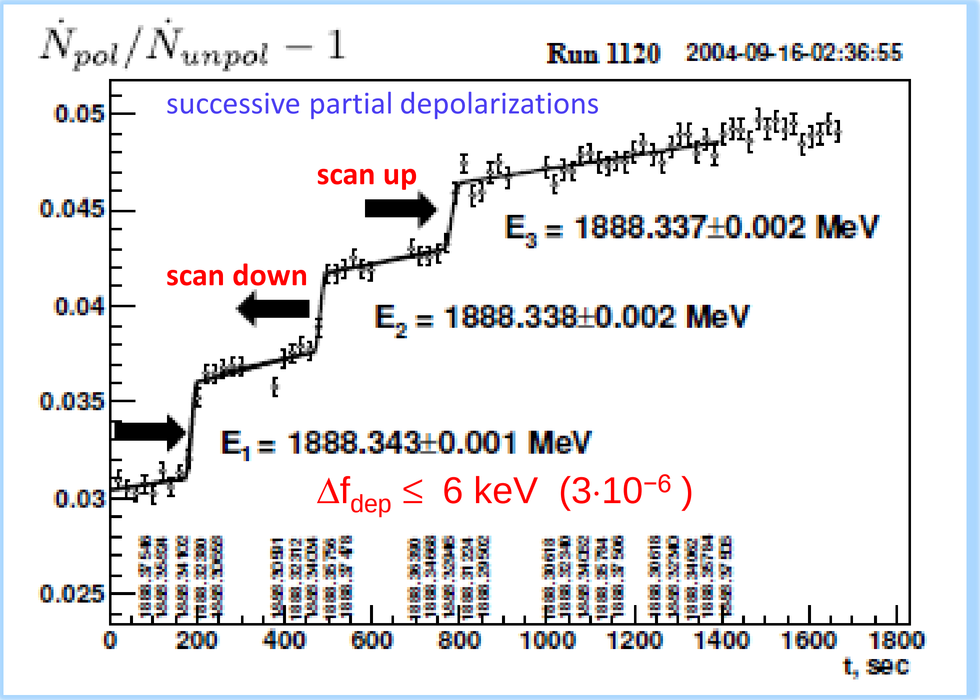
$$\Delta\left(\frac{\dot{N}_{pol} - \dot{N}_{unpol}}{\dot{N}_{pol}}\right) \propto \varsigma^2$$

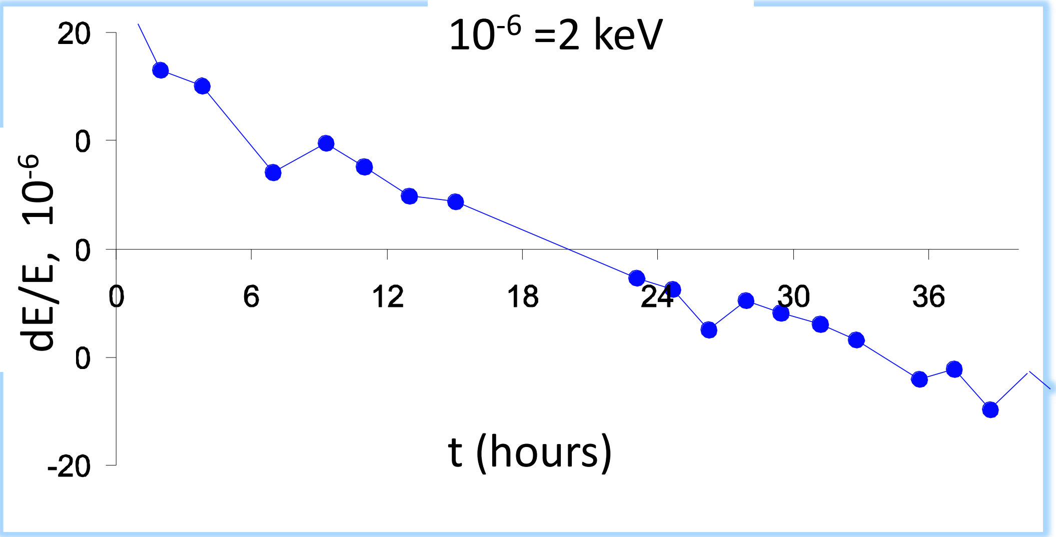


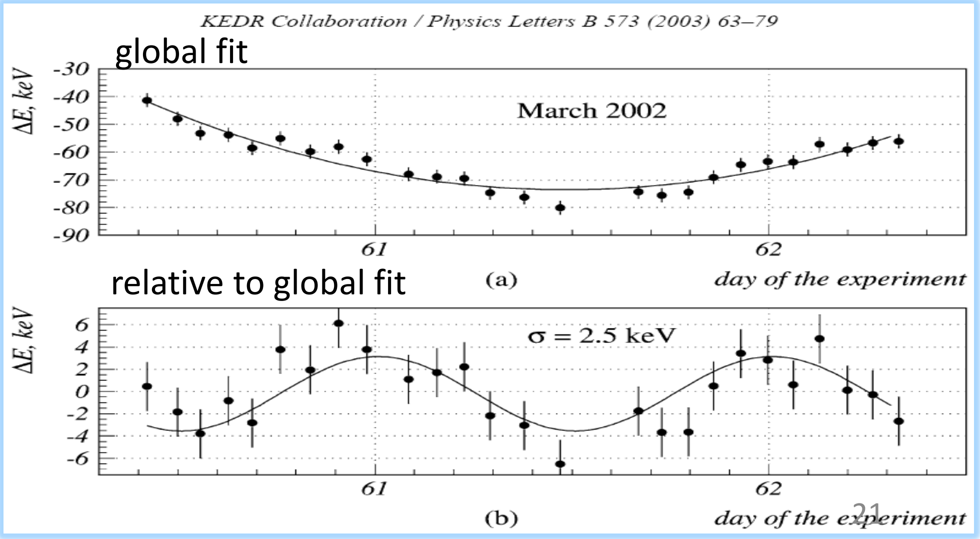
- Touschek electron counting rate up to ~ 1 MHz/mA
- Touschek fraction in total rate ~ (60-80) %; jump (1÷2) %
- Common Rb standard (10^{-10}) of frequency for VEPP-4M RF system master clock and depolarizer synthesizer to exclude their drifts relative to each other
- Revolution frequency stability $\Delta\omega_0/\omega_0 \sim 10^{-10}$ means energy stability (if no any other reasons) $\Delta E/E \sim \alpha^{-1}\,\Delta\,\omega_0/\omega_0 \sim 6\cdot 10^{-9}$ (m.c.f. $\alpha = 0.0017$)
- Typical accuracy ~10^{-6}

SUPPRESSION OF SIDEBAND RESONANCES AND ENERGY LONG-TERM STABILITY AT VEPP-4M









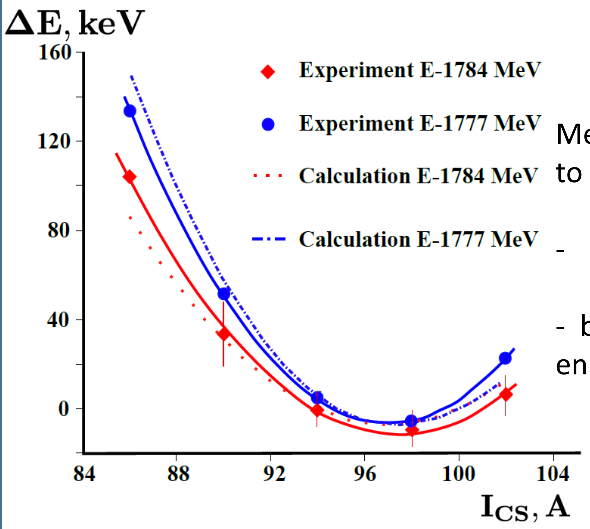
MASS MEASUREMENTS WITH RD AT VEPP-4 AND VEPP-4M

Particle	E, MeV	Detector	Years
J/ψ	3096.93±0.10	OLYA	1979-1980
ψ(2S)	3685.00±0.12	OLYA	1979-1980
Υ	9460.57±0.09±0.05	MD-1	1983-1985
Υ’	10023.5±0.5	MD-1	1983-1985
Υ’’	10355.2±0.5	MD-1	1983-1985
J/ψ	3096.900 ± 0.002 ± 0.006	KEDR	2002-2008
ψ(2S)	3686.099 ± 0.004 ± 0.009	KEDR	2002-2008
ψ(3770)	3779.2 (+1.8-1.7) (+0.6-0.8)	KEDR	2002-2006
D^0	1865.30 ± 0.33 ± 0.23	KEDR	2002-2005
D^+	1859.53 ± 0.49 ± 0.20	KEDR	2002-2005
τ	1776.81 (+0.25-0.23) ± 0.15	KEDR	2005-2008

Top list of mass accuracy

Particle	δM/M
n	3.9×10^{-8}
p	4.0×10^{-8}
e	4.1×10^{-8}
μ	9.0×10^{-8}
$\pi^{\pm}$	2.5×10^{-6}
ψ(2S)	**3.0×10^{-6}**
J/ψ	**3.5×10^{-6}**
π^0	4.4×10^{-6}

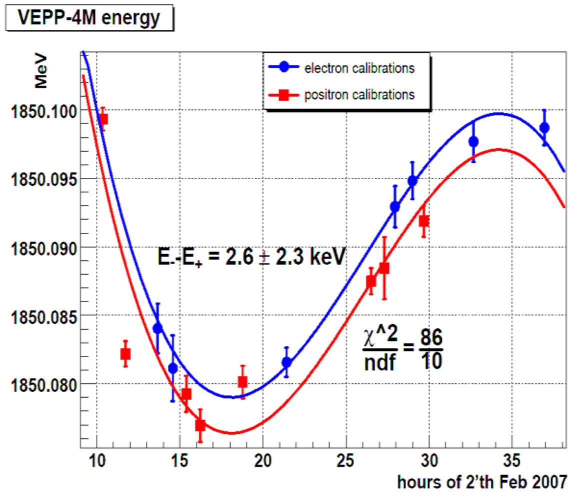
EXAMPLES OF STUDY OF ACCURACY ISSUES



Measurement of spin tune shift related to **decomp**ensation of KEDR solenoid:

- optimal anti-solenoid (AS) current found;
- betatron coupling (~1% in AS current) and energy error (down to ~1 keV) minimization

Distinct-in-time comparison: measured beam energy in series of consecutive calibrations of e^+ and e^- with electrostatic orbit bumps ON



Systematic uncertainties in J/ψ scans (keV):

Uncertainty source	2002	2005	2008	Common
Energy spread variation	3.0	1.8	1.8	1.8
Energy calibration accuracy	1.6	1.9	1.9	1.6
Energy assignment to DAQ runs	3.7	3.5	3.5	2.5
Beam separation in parasitic I.P.s*	0.9	1.7	1.7	0.9
Beam misalignment in the I.P.	1.8	1.5	1.5	1.5
e^+-, e^--energy difference	1.2	1.3*	1.2	1.2
Symmetric distortion of the energy distribution	1.5	1.3	2.1	1.3
Asymmetric distortion of the energy distribution*	2.1	1.9	1.9	1.9
Beam potential	1.9	1.9	1.9	1.9
Detection efficiency instability	2.3	1.7	1.8	<0.1
Residual machine background	1.0	0.7	0.7	<0.1
Luminosity measurements	2.2	1.7	1.7	1.1
Interference in the hadronic channel	2.7	2.7	2.7	2.7
Sum in quadrature	≈ 7.7	≈ 7.0	≈ 7.2	≈ 5.8

* — correction uncertainty

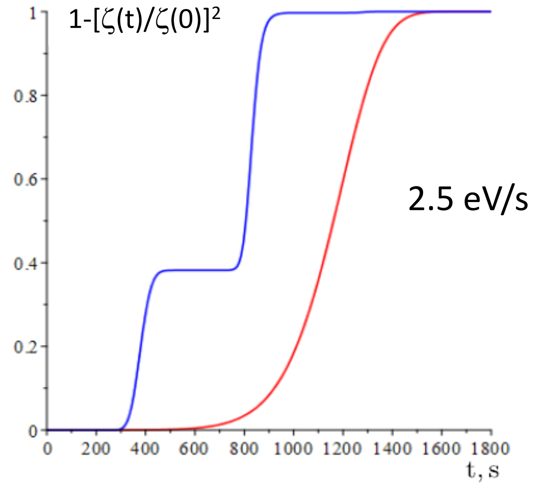
Andrey Shamov, ϒ(1S)-ϒ(3S). Workshop on e+e- collisions from Phi to Psi, ShangHai, China, August 2022

FINE SCANNING

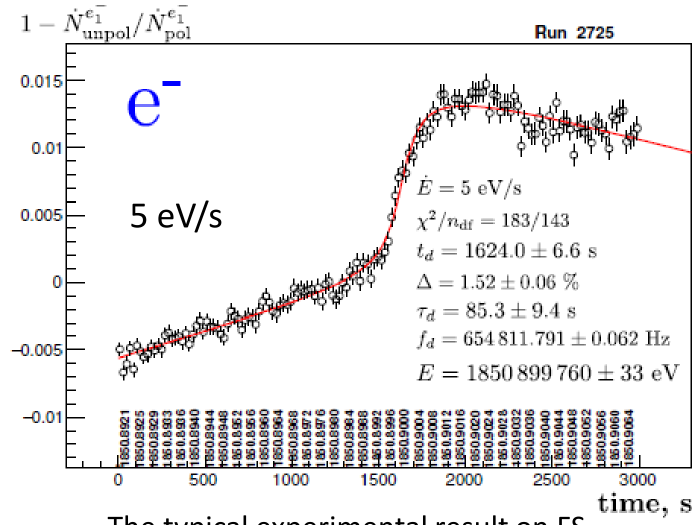
The correctness of approaches to the choice of modes and scanning parameters was most clearly confirmed in experiments on Fine Scanning.

Multiple fast crossing the resonance due to energy diffusion: $2\pi|w_k|^2 \ll \varepsilon_\nu \lambda_\gamma$

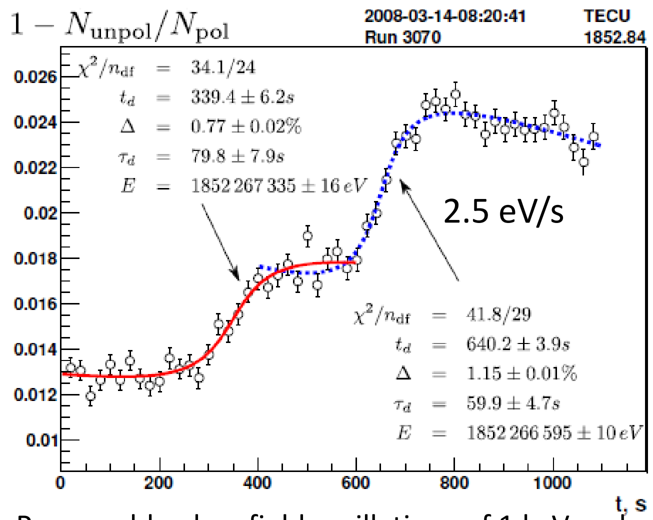
Prolonged ("long-drawn") depolarization process: $\frac{d\varsigma}{dt} = -\zeta\pi\omega_0|w_k|^2 f[\epsilon(t)]\ ;\ \epsilon(t) = \epsilon(0) + \int_0^t \dot{\epsilon}_{dep} dt + \delta\epsilon(t);\ f[\epsilon(t)] \approx \frac{1}{\sqrt{2\pi\varepsilon_\nu}} \exp\left(-\frac{\epsilon^2}{2\varepsilon_\nu^2}\right)$



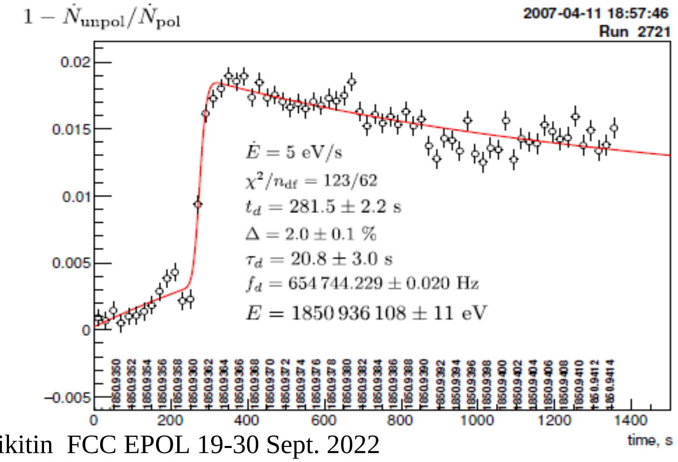
Model. Spin linewidth 1 keV; $|w_k|=10^{-7}$.
Blue: energy oscillations of 2 keV and 500 s



The typical experimental result on FS.



Presumably, slow field oscillations of 1 keV and a period of a few hundred seconds.

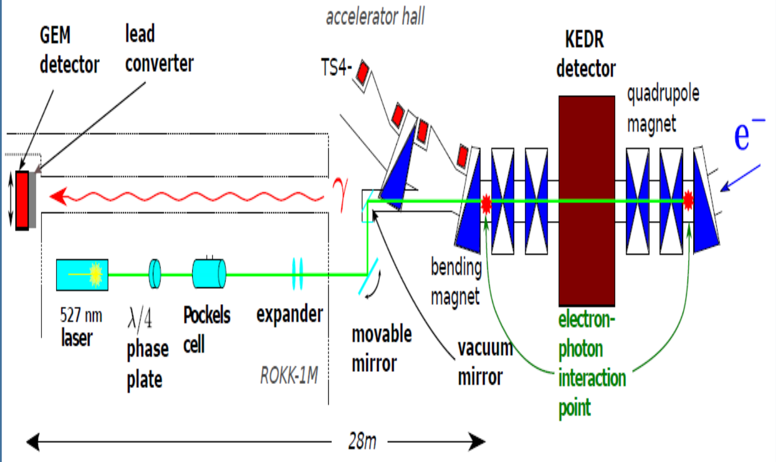


The rare case of a sharp jump, presumably, due to oncoming energy drift. Depolarization frequency resolution is found as the ratio of the fit error of 1.96 eV to the beam energy of 1852 MeV and is approximately 10^{-9} (relevant to check CPT invariance when comparing e+ and e- spin frequencies).

"Long-drawn" depolarization is not desired in the viewpoint of RD efficiency. It takes place if the depolarizer line is much smaller than the spin linewidth. To our experience, the optimal case is when the widths of both lines are approximately the same and do not exceed the required energy error.

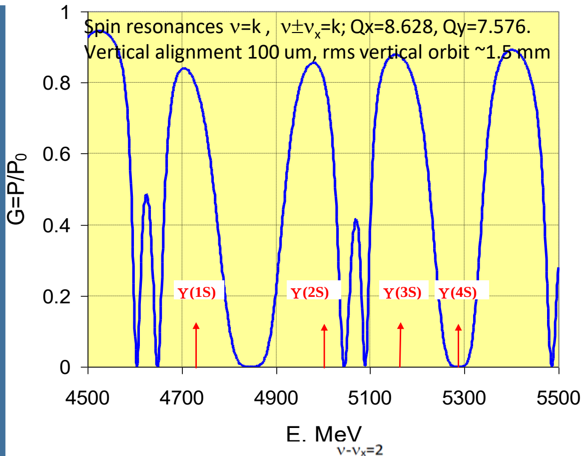
WHAT IS CURRENTLY WITH RD AT VEPP-4M?

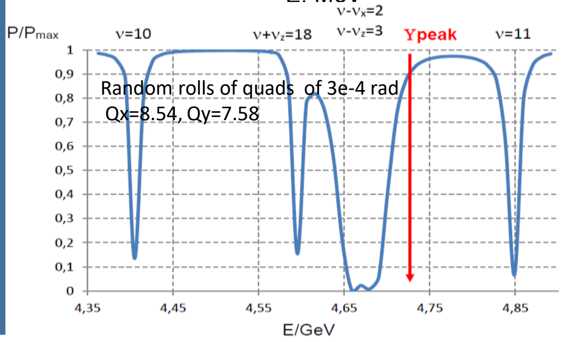
Layout of the laser polarimeter:



V. E. Blinov *et al.*, JINST **15** (2020) C08024

Stepan Zakharov' talk at EPOL 2022 last week





- To study the magnitude of the spread in the readings of RD in alternating scanning up and down.
- Comparing with theoretical estimates of the effect of various factors: measured (temperature changes, drift and pulsations of the guide field, instability in the position of the radial orbit) and as well as calculated (quadratic nonlinearity, radiative diffusion of the spin precession phase).

Forthcoming experiment at KEDR/VEPP-4M

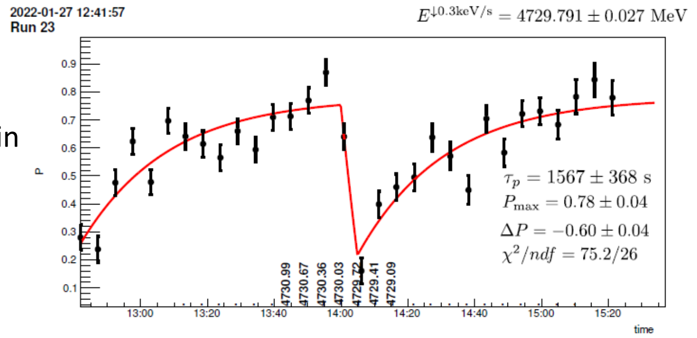
Status of preparation:

- Test scan of $\Upsilon(1S)$ without beam energy measurement was done
- Work to improve energy stability of VEPP-4M
- Polarization was obtained at $E_{beam} = 4.73$ GeV
- Laser polarimeter is in operation
  - First dozen of energy calibrations were done
  - Works to improve performance are in progress
  - Study of systematic uncertainties started (polarimeter+accelerator)

Example of energy calibration with the new polarimeter:

E=4.73 GeV

τ_p(S-T)=40 min



★ Hope to start experiment in 2023

Goals for $\Upsilon(1S)$:

- Systematic uncertainties < 30 keV (6.3 ppm)
- Statistical uncertainty on mass $M < 40$ keV
- Statistical uncertainty on electronic width $\Gamma_{ee} < 1\%$

Luminosity $\simeq 10$ pb^{-1}, $\simeq 200$ runs, optimistic time estimate $\simeq 2$ months

Andrey Shamov, Υ(1S)-Υ(3S). Workshop on e+e- collisions from Phi to Psi, ShangHai, China, August 2022

BROADENING OF SPIN LINEWIDTH

$\varepsilon_\nu \sim \nu \langle H'' (\sigma_{x\beta}^2 + \sigma_{x\gamma}^2) \rangle$ broadening of spin line due to sextupoles [turn^{-1}]

$\varepsilon_{diff} \sim \frac{\sigma_\nu}{\nu_\gamma} \frac{\lambda_\gamma}{2\pi}$ broadening of spin line due to radiative diffusion of spin phase [turn^{-1}]

V. Blinov, E. Levichev, S. Nikitin and I.Nikolaev. Eur. Phys. J. Plus (2022) 137:717

	E, GeV	f_0 kHz	σ_ν instant spin tune spread due to energy spread [turn^{-1}]	ν_γ synchrotron tune [turn^{-1}]	σ_ν/ν_γ modulation index	$\lambda_\gamma/2\pi$ radiation decrement [rad^{-1}]	ε_ν [turn^{-1}]	ε_{diff} [turn^{-1}]	$\frac{\sqrt{\varepsilon_\nu^2 + \varepsilon_{diff}^2}}{\nu}$
VEPP-4M	1.85 4.73	820	0.0015 0.0098	~0.01 0.015	~0.015 ≈0.7	1.8e-6 3.0e-5	~4e-6 ~1e-6	2.7e-7 2.1e-5	≈1e-6 ≈2e-6
LEP	45.6	11	0.061	0.083	0.73	4.7e-4	-	3.4e-4	~3e-6
FCC-ee	45.6	3	0.039	0.025	1.56	1.25e-4	~7.3e-5	2e-4	≈2.3e-6

VEPP-4M: the estimates are consistent with the data of numerous experiments

LEP: the width ε_{diff} =3.4e-4 (ΔE=150 keV) doesn't contradict the RD experiment with achieved precision of 2 ppm

FCC-ee: the depolarizer linewidth should be of no more than 100 keV (2.2 ppm in energy); the relative spin line width $\delta\nu/\nu \sim \nu^{-1}\sqrt{\varepsilon_\nu^2 + \varepsilon_{diff}^2}$ ≈2.3e-6 is relevant

NOTES ON USE OF RD AT ELECTROWEAK e+e- FACTORIES

- As in the practice of VEPP-4M, the same quantum frequency standard should be used for both the RF system and for depolarizer synthesizer. For FCC-ee and CEPC, the required stability of the reference signal is estimated at a level of at least $\alpha\Delta E/E \sim 10^{-11}$ at $\alpha \sim 10^{-5}$ and designed error in determining the energy $\Delta E/E \sim 10^{-6}$.

- Depolarizer linewidth $\delta\nu_d = \delta f_d / f_0$ should be approximately equal to the width of the spin line estimated from influence of quadratic nonlinearity and radiative diffusion of the spin precession phase $\sqrt{\varepsilon_\nu^2 + \varepsilon_{diff}^2} \approx 2.4\cdot 10^{-4}$.

- Simultaneous use of two selective depolarizers, acting independently on two "pilot" bunches. Frequency scanning in mutually opposite directions. This can reduce systematic error caused by the collider energy drift and broadening of spectral lines.

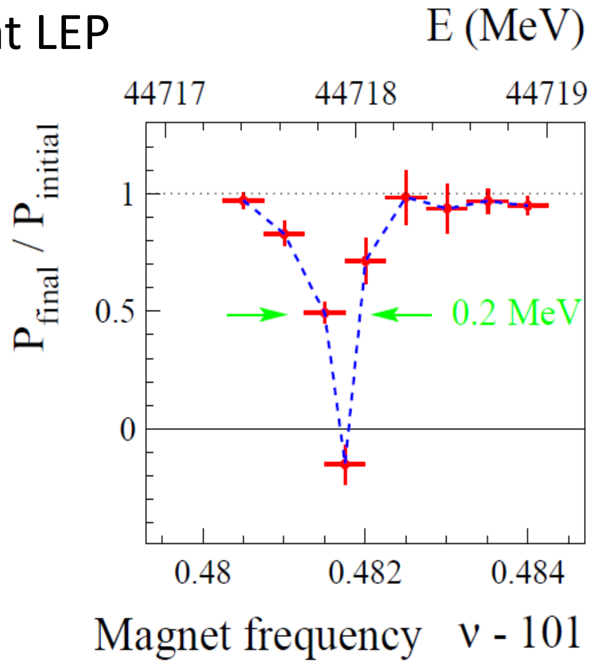
- It is easy to prevent parasitic RD events, since all side band resonances caused by synchrotron modulation and low-frequency field pulsations are far from the main one and rather weak.

Width of excited spin resonance at LEP

L. Arnaudon et al. CERN SL/94-71 (BI)

spin tune sweeps of $\Delta\nu = 0.001$
energy span equivalent to sweeping ~10^{-5} at Z pole
instantaneous precision of 2 ppm, i.e. $\Delta\nu = 0.0002$, $\nu = 103.5$
time for sweep ~ 1 min
depolarization maximum didn't change when synchrotron tune was varied, but properly changed with shift in RF frequency

Obtained accuracy is in accordance with our estimate of spin linewidth for 45 GeV LEP



FCC-ee DEPOLARIZER: CONCEPTUAL EXAMPLE (preliminary)

Depolarizer linewidth $\delta f_d^* \approx \rho \Delta E \approx 1$ Hz is artificially made using synthesizer ($\Delta E = 100$ keV). Scanning proceeds at average rate $\langle df_d/dt \rangle$, which makes much smaller contribution to line broadening $\sqrt{\langle df_d/dt \rangle} \ll \delta f_d^*$, but nevertheless provides relevant total scanning time in assumed energy interval.For instance, ~ 10 minutes per scan span of 1 MeV or 7 Hz, $\langle df_d/dt \rangle \approx 0.01$ Hz/s. These features are associated with small value of specific scan scale $\rho = 0.007$ Hz/keV at FCC-ee. For comparison, $\rho \approx$ 2Hz/keV at VEPP-4M.

FCC-ee TEM depolarizer concept at $E = 45.6$ GeV:

spin harmonic amplitude $|w_k| \propto \dfrac{\nu U L |F^\nu|}{E d}$

depolarization time $\tau_d \approx \dfrac{\delta f_d^*}{4\pi |w_k|^2 {f_0}^2}$

strip-line length $L = 1$ m; gap $d = 20$ mm

amplitude of voltage between plates $U = 100$ V

spin response factor $|F^\nu| = 5$; $|w_k| = 1.8\ 10^{-5}$

$f_0 = 3$ kHz; $\nu = 103.5$; $\delta f_d^* = 1$ Hz

τ_p=256 h; "uncorrelatedness" $\nu^2 \gg \tau_p (\delta f_d^*)^3 / {f_0}^2$

and "rapidity" $(\delta f_d^* / f_0)^2 \gg |w_k|^2$ satisfied

bunch depolarized in $\tau_d \approx 28$ second

time for polarization measurement in one point $\tau_m \sim \tau_d$

Parameters are given for scaling and can be changed depending on, for instance, time τ_m required foraccurate measurement of pilot bunch polarization

SUMMARY

More than 3500 RD calibrations of beam energy performed at VEPP-4M using Touschek polarimeter. Various modes of RD were studied.

At present, methodical experimental studies are being carried out on RD at VEPP-4M with a laser polarimeter in connection with the forthcoming measurement of the upsilon meson mass.

Numerous experiments at VEPP-4M in comparison with calculations make it possible to evaluate the features of the use of RD at future Electroweak Factories FCC-ee and CEPC

We compare VEPP-4M, LEP and FCC-ee in terms of the main factors affecting the accuracy of determination of the instantaneous position of the spin resonance.

Preliminary estimates show that the RD accuracy for FCC-ee in the Z- peak might be reached at the same level of 10^{-6} , as it was at LEP (45 GeV) or in regular calibrations at VEPP-4M (below 2 GeV).

THANK YOU FOR YOUR ATTENTION!