Resonance depolarization method

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Outline

Introduction

- Precision measurement of the mass of the elementary particles in colliding experiments requires precise beam energy calibration

Resonace depolarization technique

- The most precise method of beam energy measurement
- $\Delta E/E \sim 10^{-6}$
- Suggested and firstly applied in BINP (Novosibirsk) at 1971
  Baier, Sov. Phys. Usp. 14 695–714 (1972)
- Used in experiments of precise mass measurement in the wide energy range
  Skrinskii, Shatunov, Sov. Phys. Usp. 32 548–554 (1989)
- Energy calibration for some synchrotron light sources: ESSY-I, BESSY-II,ALS,SLS, ANKA, *SOLEIL*

Used in experiments of precise mass maeasurement

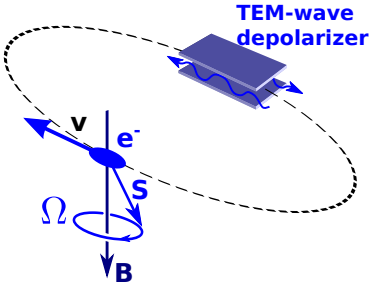
Particle	Experiment		Date
Φ, $K^{\pm}$	VEPP-2M	OLYA	1975-1979
J/ψ, $\psi(2S)$	VEPP-4	OLYA	1980
$\Upsilon(1S)$,$\Upsilon(2S)$,$\Upsilon(3S)$	VEPP-4	MD-1	1982-1986
$\Upsilon(1S)$	CESR	CUSB	1984
$\Upsilon(2S)$	DORIS II	ARGUS, Crystal Ball	1983
K^0, ω	VEPP-2M	CMD	1987
Z	LEP	ALEPH, DELPHI, L3, OPAL	1993
J/ψ, $\psi(2S)$, τ, D^0, $D^{\pm}$ $\psi(3770)$	VEPP-4M	KEDR	2003-2015

The idea of the method

Spin precession

Frenkel,Thomas (1926),
Bargmann, Michel, Telegdi (1959)

$$\frac{ds^i}{d\tau} = 2\mu F^{ij} s_j - 2\mu' u^i F^{jk} u_j s_k$$



$$\frac{d\vec{s}}{dt} = \overbrace{2\mu \frac{\vec{s} \times \vec{B}'}{\gamma}}^{\text{dynamic}} + \overbrace{(\gamma - 1)\frac{\vec{s} \times [\vec{v} \times \dot{\vec{v}}]}{v^2}}^{\text{kinematic (Thomas) precession}} = \vec{\Omega} \times \vec{s}$$

$$\Omega = \omega_0 \left(1 + \gamma \frac{\mu'}{\mu_0}\right) = \omega_0 n \pm \omega_d, \quad n \in \mathbb{Z}$$

$$\delta(\mu'/\mu_0) \approx 2.3 \times 10^{-10} \quad \delta m_e \approx 2.2 \times 10^{-8}$$

$$E = (440.6484431 \pm 0.0000097)\,[\text{MeV}] \times \left(n - 1 \pm \frac{\omega_d}{\omega_0}\right)$$

Energy calibration accuracy

1. Measurement of the spin precession frequency by resonance depolarization ($\sim 1keV$)
2. Calculation of average beam energy ($\sim 2keV$)
3. Calculation of average beam energy at the interaction point ($\sim 1keV$)
4. Calculation of luminosity wighted average c.m. energy ($\sim 1keV$)

More about corrections and errors to center of mass energy

Bogomyagkov, et al., RUPAC-2006-MOAP02.
Nikitin, RUPAC-2006-MOAP01.
Bogomyagkov, et al., Conf. Proc. C 070625 (2007) 63.

Radiative polarization

Sokolov-Ternov effect (1963)

Sokolov, Ternov, Dokl.Akad.Nauk SSSR 153 (1963) no.5, 1052-1054

Intensity of SR with spin flip

$$W^{\uparrow\downarrow} \approx W_0 \frac{4}{3}\left(\frac{\omega_c}{E}\right)^2$$

$$\tau_p = P_0 \frac{\lambda\!\!\!^{-}_C}{\alpha c}\frac{1}{\gamma^2}\left(\frac{H_0}{H}\right)^3 \qquad P_0 = \frac{8\sqrt{3}}{15} \approx 92.4\%$$

First observation

- VEPP-2 (Novosibirsk) in 1970

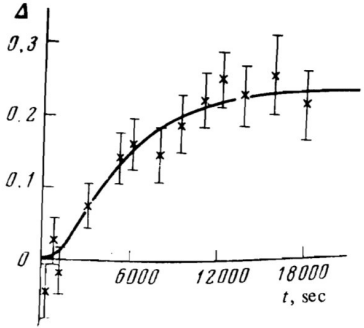
  Baier, Sov. Phys. Usp. 14 695–714 (1972)

- ACO storage ring (Orsay) in 1972

  Duff, Marin, Masnou, Sommer, Preprint, Orsay 4-73(1973)

Radiative polarization at VEPP-2M observed with Touschek polarimeter, $\tau = 70$ min (1974)

Serednyakov, Skrinskii, Tumaikin, Shatunov, JETP, V44, No. 6, p.1063 (1976)



$$P(t) = P\frac{\tau}{\tau_p}\left(1 - e^{-t/\tau}\right); \quad \tau = \frac{\tau_d \tau_p}{\tau_p + \tau_d}$$

Depolarizing resonances

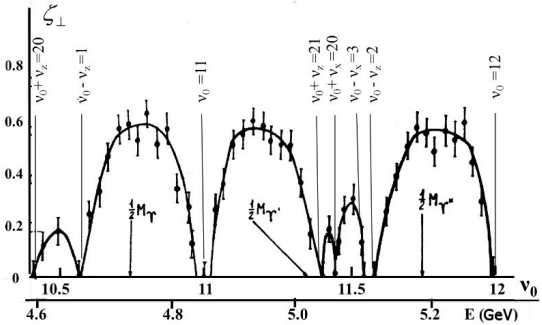
$$\nu = \frac{\Omega}{\omega_0} - 1 = k \cdot \nu_x + l \cdot \nu_y + m \cdot \nu_s + n \quad k, l, m, n \in \mathbb{Z}$$

- Stochastic depolarization

$$\tau_d \sim \left(\nu_0^2 \sum \frac{|w_k|^2}{(\nu_0 - \nu_k)^4} \right)^{-1}$$

- Difficult to accelerate polarized beam due to resonance cross
- Spin precession shift

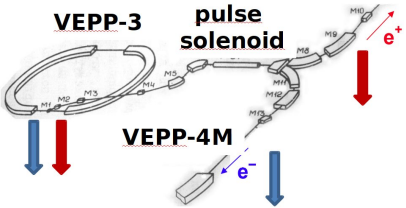
$$\delta\nu \sim \frac{1}{2} \sum \frac{|w_k|^2}{\nu_0 - \nu_k}$$



Equilibrium polarization degree measurement at VEPP-4 with laser polarimeter.

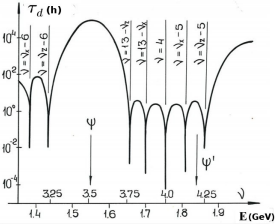
Obtaining polarization at VEPP-4M

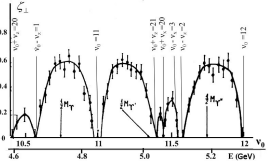
Polarized beam injection into VEPP-4M ring



Polarization time

Ring	VEPP-3	VEPP-4M
τ_p [h]	$\frac{12}{E[GeV]^5}$	$\frac{1540}{E[GeV]^5}$
τ_p @ 1.55 GeV	1.34 h	172 h
τ_p @ 1.85 GeV	0.56 h	71 h
τ_p @ 4.1 GeV		80 min
τ_p @ 4.73 GeV		39 min





- Good beam polarization for J/ψ, $\psi(2S)$, $\Upsilon(1S)$, $\Upsilon(3S)$
- Problem with τ lepton energy region (close to integer $\nu = 4$ resonance)

Polarization measurement

- Fixed target
  - Mott scattering (spin orbit coupling, $100kev < E < 5$ MeV): JLab
  - Moller scattrinc (atomic electron, $\lesssim 1$ GeV): JLab, BINP,...
- Touschek (intrabeam scattering) polarimeter (BINP, BESSY-I/II, ALS, SLS...). Best for lower energies $E < 2$ GeV
- Compton backscattering (better for high energies $E > 5GeV$)
  - laser: Cornell (CESR), DESY (DORIS), BINP (VEPP-4), SLAC (SLD) ...
  - synchrotron light from clashing (positron) beam: BINP (VEPP-2M, VEPP-4)
- Synchrotron spin-light: BINP (VEPP-4)
- ...

Touschek polarimeter

- Proposal to use beam lifetime to detect polarization in 1968 (flat beam calculation)

  Baier, Khoze, Atomnaya Énergiya, V25, No.5, pp. 440–442 (1968)

- Tumaikin's proposal to use scint. counters (1970)
- Calculation for 2D beam

  Serednyakov, Skrinskii, Tumaikin, Shatunov, JETP, V44, No. 6, p.1063 (1976)

- With some relativistic corrections (1978)

  Baier, Katkov, Strakhovenko, Dokl.Akad.Nauk SSSR, 1978, V241,No4, P.797–800

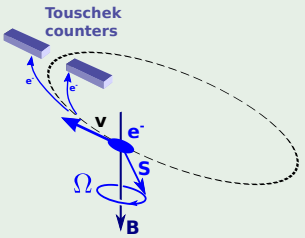
- with Coulomb effects (1978)

  Baier, Katkov, Strakhovenko, Dokl.Akad.Nauk SSSR, 1978, V241,No4, P.797–800

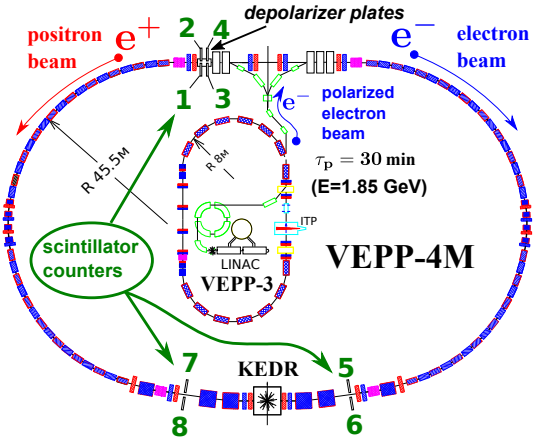
Itra-beam scattering ($e^-e^- \to e^-e^-$) scattering

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

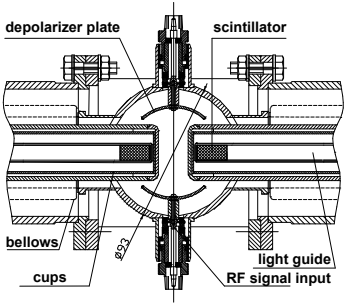
$$\frac{dN}{dt} \approx A\frac{N^2}{V\gamma^2(\Delta p/p)^2}(1 - P^2\eta)$$

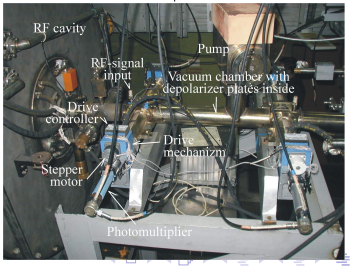


Touschek polarimeter at VEPP-4M



8 movable scintillator counters located inside vacuum chamber at different places of VEPP-4M



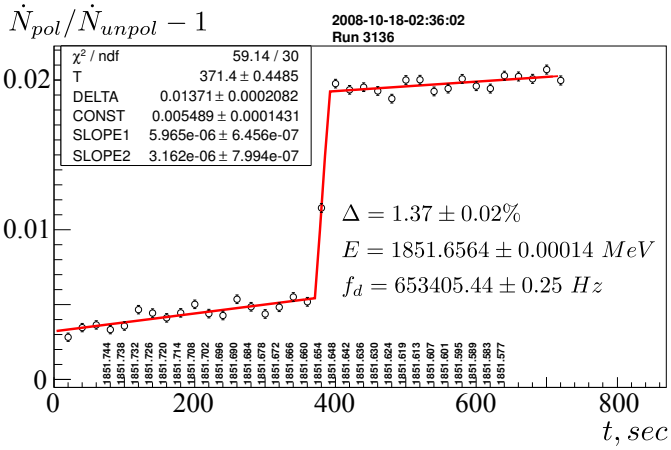


Touschek polarimeter at VEPP-4M

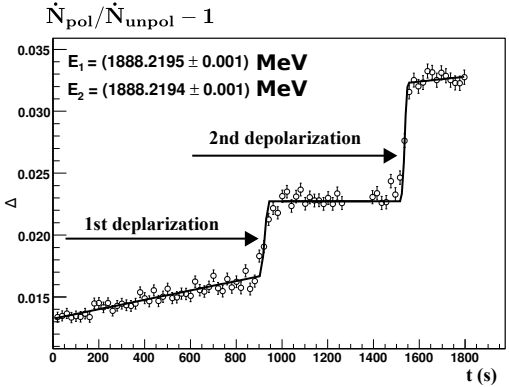
System performance

Energy range	$1.5 \div 2.0\,\mathrm{GeV}$
Beam current	$> 0.1\,\mathrm{mA}$
Number of bunches (electron or positron)	4
Count rate	$1\,\mathrm{MHz}$ ($50\,\mathrm{kHz/mA^2}/\mathit{counter}$)
Compensation technique	$\Delta = \dot{N}_{pol}/\dot{N}_{unpol} - 1$
Depolarization effect	$\Delta = 1 \div 3\,\%$
Polarization degree	$\approx 80\%$
Stat accuracy	$1\,\mathrm{keV}$ (10^{-6})
Number of calibration at same bunches	3
Calibration duration	2 hours
Number of energy calibrations since 2001	≈ 4000

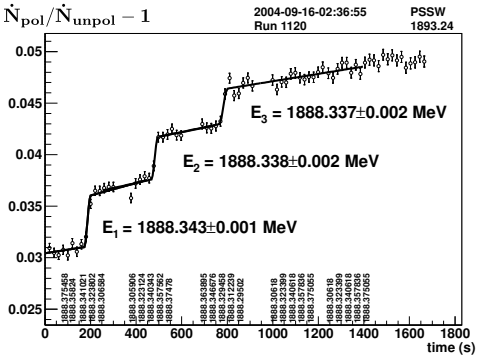
Energy calibration example



Several calibrations with same polarized bunch



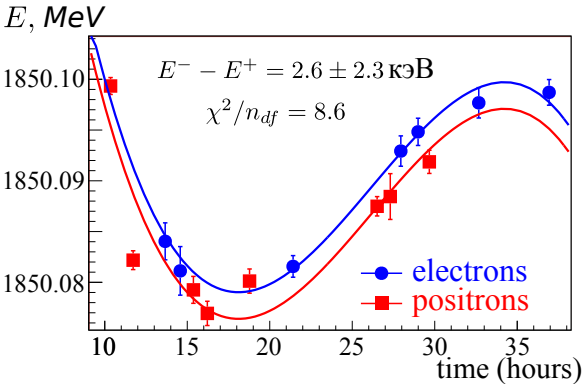
Double jump



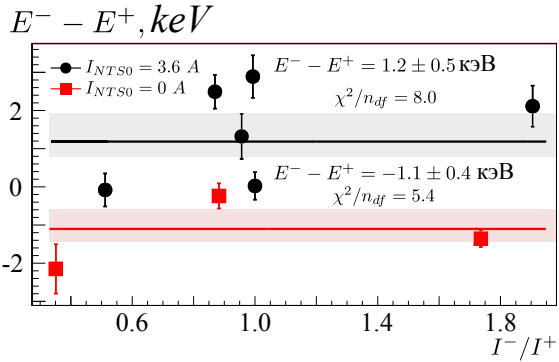
Triple jump

Double up-down scan increase reliability of energy calibration.
Suppress cases of calibration at side 50 Hz spin resonances

Electron and positron energy comparison



serial interlaced e^-/e^+ energy calibrations



simultaneous e^-/e^+ energy calibrations

Investigating systematics of energy calibration for J/ψ, ψ' mass measurement experiment

Energy calibration accuracy

Single beam energy measurement error

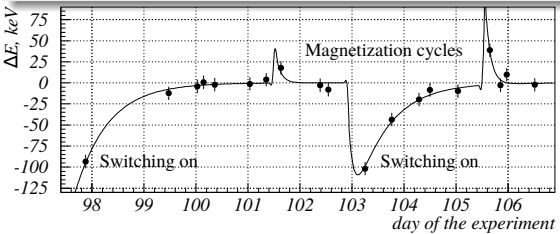
source	ΔE, keV
Precession frequency measurement	± 1.0
Spin resonance width	2.0 ± 1.0
Vertical close orbit disturbances	-0.4 ± 0.3
Coherent loss asymmetry	0.1
KEDR longitudinal field compens.	0.1
total	1.5 keV (10^{-6})

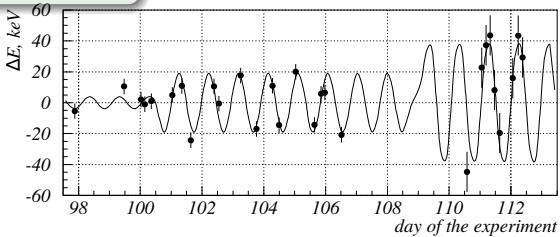
Energy interpolation between calibrations

Energy prediction function

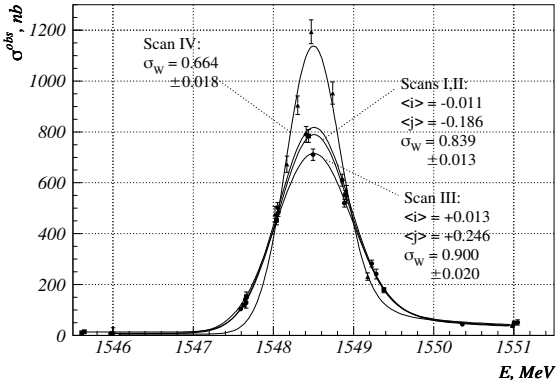
$$E = \alpha_H \cdot H_{\mathrm{NMR}} \cdot (1 + \alpha_T \cdot (T_{\mathrm{ring}} - T_{\mathrm{NMR}})) \times f(T_{\mathrm{ring}}, T_{\mathrm{air}}, T_{\mathrm{water}}) +$$
$$+ A(t) \cdot \cos\left(\frac{2\pi t}{\tau_{\mathrm{day}}} - \varphi(t)\right) +$$
$$\delta E_{\mathrm{on}} \cdot \exp\left(-\frac{t_{\mathrm{on}}}{\tau_{\mathrm{on}}}\right) + \delta E_{\mathrm{cycle}} \cdot \exp\left(-\frac{t_{\mathrm{cycle}}}{\tau_{\mathrm{cycle}}}\right) + E_0(\Delta i, t),$$

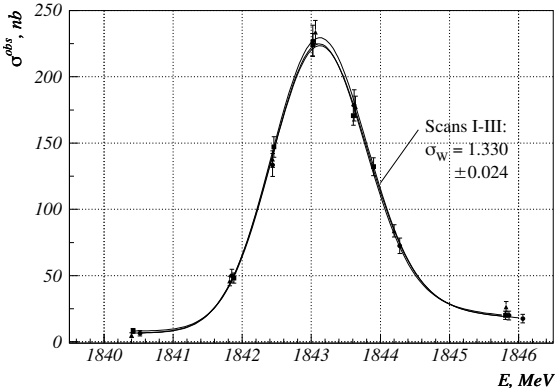
Energy prediction 6 ÷ 8 keV with 218 energy calibrations





J/ψ (0.7, pb^{-1}), $\psi(2S)$ (1.0 pb^{-1}) mass measurement with KEDR detector





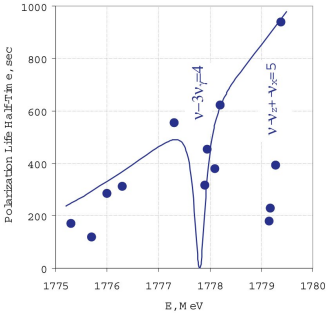
$$M_{J/\psi} = 3096.900 \pm 0.002 \pm 0.006\ MeV$$

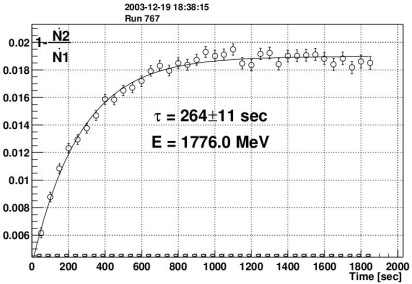
$$M_{\psi(2S)} = 3686.099 \pm 0.004 \pm 0.009\ MeV$$

KEDR Collaboration / Phys.Lett.B 573 (2003) 63–79
Anashin et al. / Phys.Lett.B 749 (2015) 50–56

Energy calibration in tau mass experiment

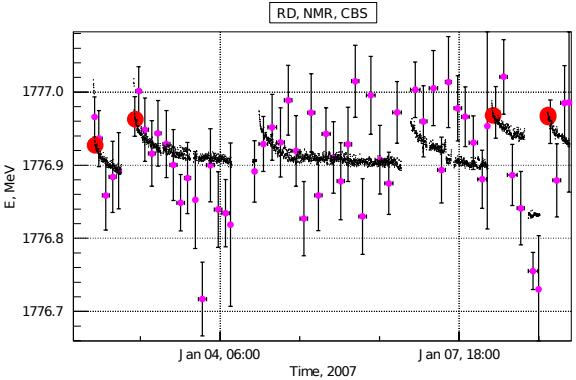
- Tau threshold (1.78 GeV) close to $\nu = 4$ integer spin resonance (E=1.76 GeV). No polarization in VEPP-3.
- Special effort to increase polarization lifetime at tau threshold were done.

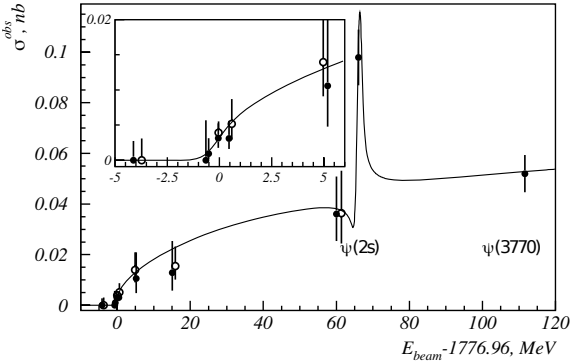




- Polarization at 1.85 GeV and deaccelerate to tau threshold
- Energy calibration after 30 min magnetic field relaxation

Energy calibration in tau mass experiment



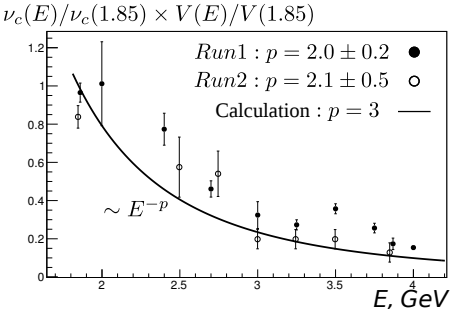


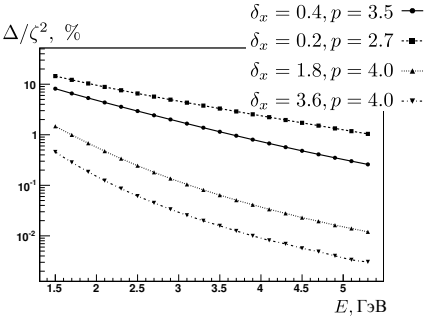
$$M_\tau = 1776.69^{+0.17}_{-0.19} \pm 0.15$$

A.G.Shamov / Nuclear Physics B (Proc. Suppl.) 189 (2009) 21–23

$$\dot{N} \propto \frac{I_{beam}^2}{E^{2\div3} V_{beam}} \propto \frac{1}{E^{5\div6}}$$

$$\Delta \approx \frac{0.5\%}{\delta q_x \delta q_y} \zeta^2 \propto \frac{1}{E^4}$$





Small count rate and polarization effect for $E = 5$ GeV

$\dot{N} \approx 10$kHz for $I = 10$ mA $\qquad \Delta \approx 0.3\%$

Need alternative method of polarization measurement

Compton backscattering polarimeter

- Suggested in BINP in 1969:

  Baier, Khoze, Sov.J.Nucl.Phys. V9, p238 (1969)

- First implemented at SPEAR (1979)

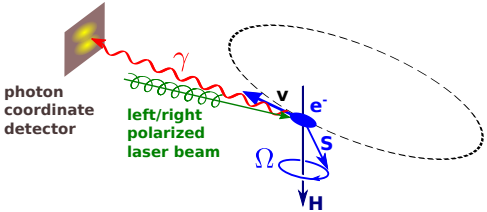
  Gustavson et al, NIM, V165, No2, p177 (1979)

- VEPP-4 (1982)

  Vorob'ev et al, Proc. All-union conference on charged particle accelerators. (1983)

- Tikhonov (1982): SR from clashing beam as source of circular polarized light
- at LEP for Z boson mass measurement (1993)

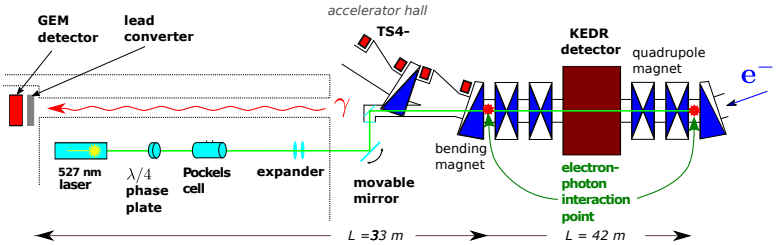
Up-down scattering asymmetry for left-right photon backscattering on vertically polarized electron beam

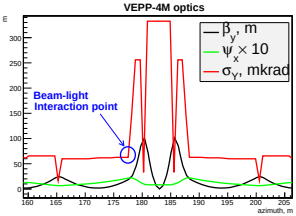


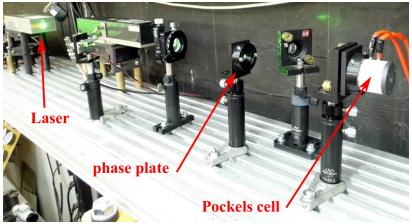
$$A = \frac{N_{\text{up}} - N_{\text{down}}}{N_{\text{up}} + N_{\text{down}}} \approx -\frac{3}{4}\frac{E\omega_0}{m_e^2} VP$$

ω_0 is the initial photon energy, V is the Stokes parameter of circular polarization (± 1)

Laser polarimeter at VEPP-4M

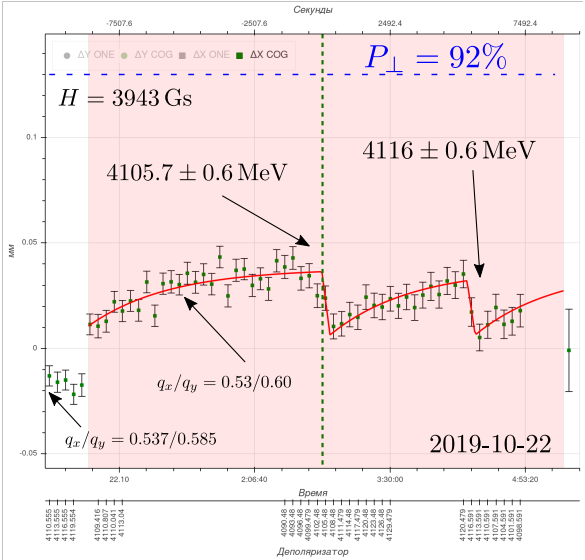






- 527 nm Nd:YLF solid state laser with 500 μJ pulse energy at 4 kHz, 6ns pulse length
- Circular polarization prepared by KD*P Pockels cell ($U_{\lambda/2} = 3.3$kV) or/and by $\lambda/4$ wave plate. Switched every pulse.
- Two-coordinate GEM detector with $2X_0$ Pb converter for gamma quanta detection.

Energy measurements by VEPP-4M laser polarimeter



$$<\Delta y> = \frac{\omega_0}{2m_e} L P_\perp \Delta V \approx 0.13\ mm$$

$$\omega_0 \approx 2.35\ eV,\ L \approx 33m,$$
$$\Delta V = 1.8 \pm 0.1$$

$$\sigma_{\Delta\langle y\rangle} = \sqrt{\frac{2}{N}\left(\frac{L}{\gamma} \oplus L\sigma_Y \oplus \sigma_y\right)} \approx \frac{7\ \mathrm{mm}}{\sqrt{N}}$$

$$\dot{N} \approx 10kHz$$

Summary

Resonace depolarization method

- Most precise method of beam energy calibration (10^{-6})

- Requires polarized beam
- Need special time to measure spin precession frequency
  - Need beam energy interpolation between calibrations. NMR,temperatures, moon phase...
- Need c.m. calculation from spin precession.

THANK YOU

Synchrotron Spin-light polarimeter

Classical synchrotron light

$$W_0 = \frac{2}{3}\frac{e^2 c}{R^2}\gamma^4$$

Magnet dipole synchrotron light

$$W_{md} = \frac{2}{3}\frac{\mu_0^2}{c^3}\omega_0^4\zeta^2 \propto \hbar^2$$

Interference between them

$$W_{mixed} = 2\sqrt{W_0 W_{md}} \propto \hbar$$

For $\omega/\omega_c > 10$, $B = 1T$, $E = 10 \div 100$ GeV

$$\delta = \frac{W_{mixed}}{W_0} \sim \zeta\omega/E \approx 10^{-4} \div 10^{-3}$$

- Suggested by Korchuganov, Kulipanov, Mezentsev (1977)
- Implemented at BINP (1982) (Belomestnykh, Bondar et al)