IBIC2024
Sept. 9-13, 2024 · Beijing, China

Laser Polarimeter at VEPP-4M Collider

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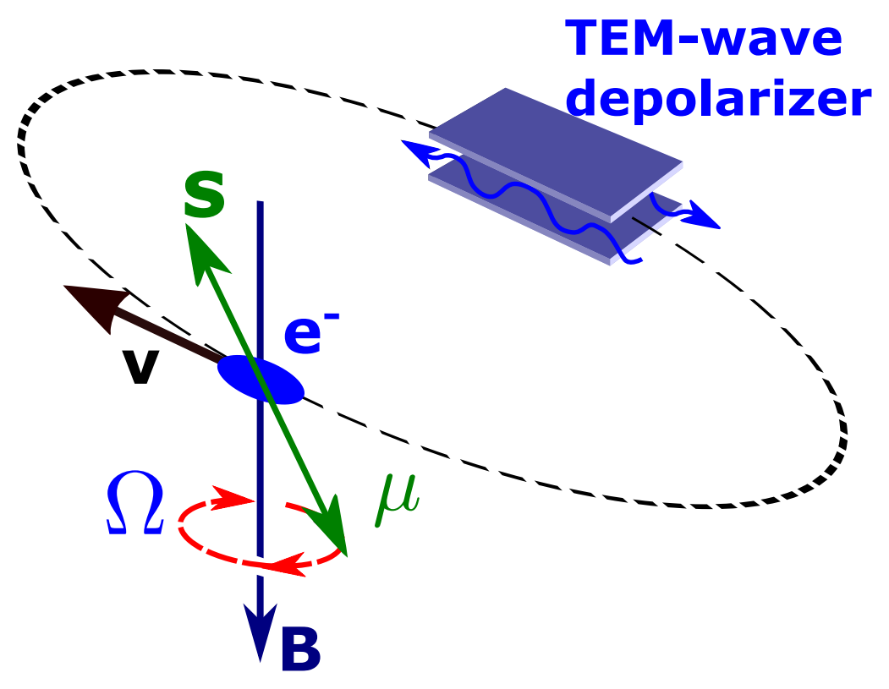
Motivation

CURRENT standard mass of the $\Upsilon(1S)$ meson is determined with accuracy of 100 keV [1](based on experimental results of VEPP-4/MD-1 and CESR/CUSB). VEPP-4M e^+e^- collider and KEDR detector (Novosibirsk, Russian Federation) are going to measure mass and leptonic width of $\Upsilon(1S)$ meson with the best achievable accuracy. To achieve Upsilon mass uncertainty of ~ 50 keV, precise electron beam energy measurement is needed. To fulfill this requirement, an installation named "Laser Polarimeter" was created at VEPP-4M collider.

Resonant depolarization method



Electron spin rotates in a guiding field of a circular accelerator [Frenkel, Thomas (1926), Bargmann, Michel, Telegdi (1959)]:

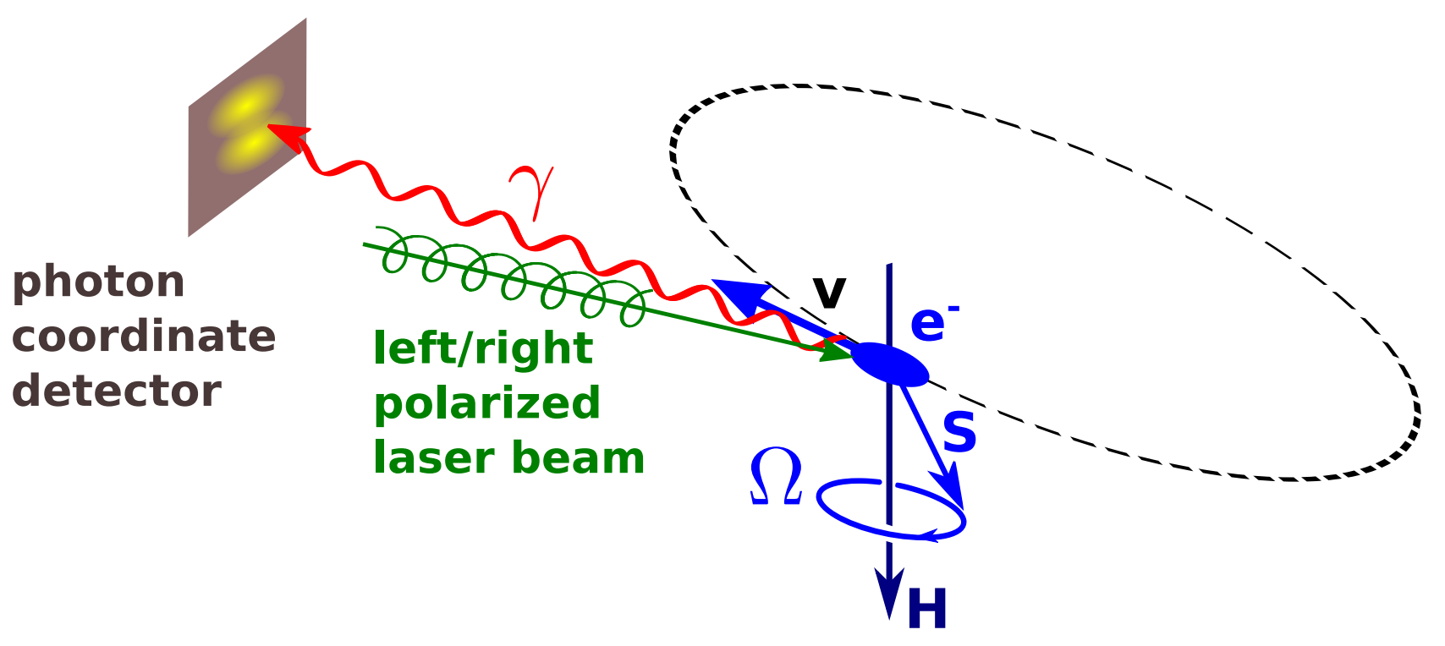
$$\Omega = \omega_0\Big(1 + \frac{E}{m_e}\frac{\mu'}{\mu_0}\Big) = \omega_0 n \pm \omega_d, \quad n \in \mathbb{Z}, \tag{1}$$

where ω_0 is revolution frequency ($2\pi 818$ kHz at VEPP-4M); m_e is electron rest energy; μ' and μ_0 are anomalous and normal part of the electron magnetic moment. When a spin-polarized electron beam is affected by the external RF field of frequency ω_d the polarized state of the beam is destroyed.
Thus, when measuring ω_d, one can calculate the electron energy:

$$E = (440.648\,462\,134 \pm 0.000\,000\,137)\,[\mathrm{MeV}] \times \times \left(n - 1 \pm \frac{\omega_d}{\omega_0}\right) \tag{2}$$

Sources of systematic uncertainty: $\delta(\mu'/\mu_0) \approx 1.03 \times 10^{-10}$, $\delta m_e \approx 2.94 \times 10^{-10}$ [PDG 2023]. Total uncertainty can be less then 10^{-6}: RD is the most precise beam energy measurement method.

Compton polarimeter



Compton backscattering cross-section depends on polarizations of initial electron and photon:

$$\frac{d\sigma(P,Q,V,\varphi,\beta)}{d\Omega} = 2\gamma^2 r_e^2\left[\frac{1}{1+\gamma^2\theta^2+\kappa}\right]^2 \times \Bigg\{\underbrace{2 + \frac{\kappa^2}{(1+\gamma^2\theta^2)(1+\gamma^2\theta^2+\kappa)} - \frac{4\gamma^2\theta^2}{(1+4\gamma^2\theta^2)^2}}_{\text{unpolarized}} \tag{3}$$

$$\underbrace{+\frac{4\gamma^2\theta^2 Q\overbrace{\cos(2[\varphi-\beta])}^{\text{quadrupole}}}{(1+4\gamma^2\theta^2)^2}}_{\text{linearly polarized}} \tag{4}$$

$$\underbrace{+\frac{2\kappa P V\gamma\theta\overbrace{\sin\varphi}^{\text{dipole}}}{(1+\gamma^2\theta^2)(1+\gamma^2\theta^2+\kappa)}\Bigg\}}_{\text{circularly polarized}}, \tag{5}$$

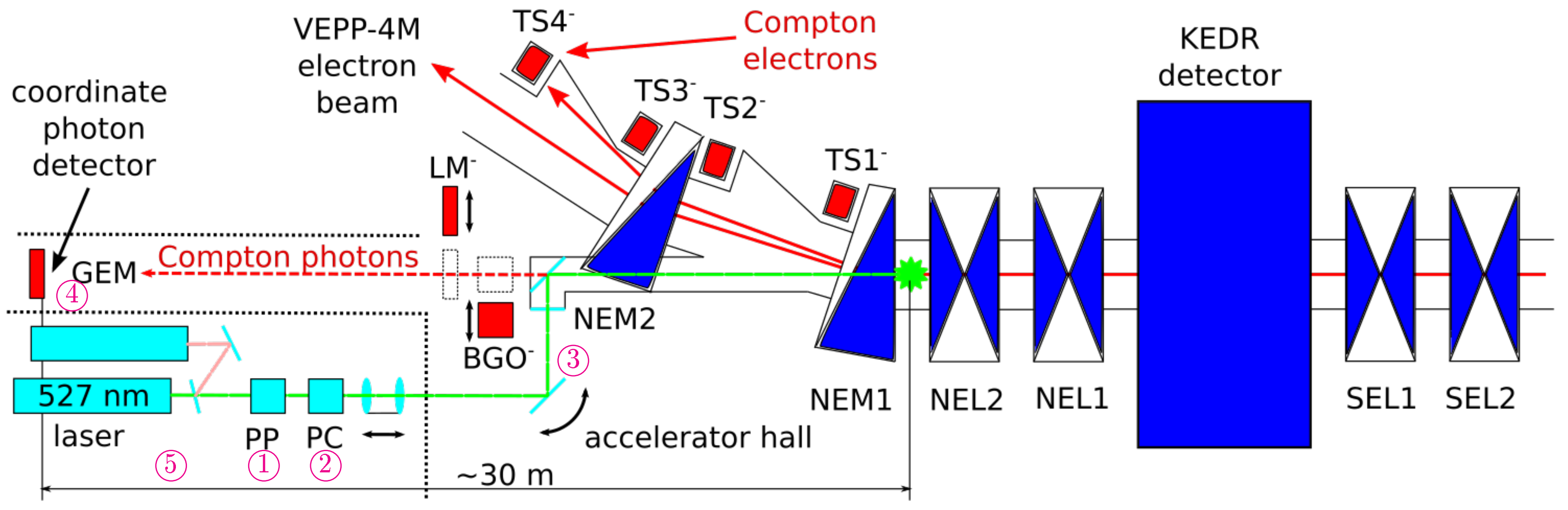
where V and Q are Stokes parameters of the photon, circular and linear polarization; β is an angle of the polarization plane; P is electron vertical polarization; $\kappa = 4\gamma\omega/m_e$ is photon "hardness", recoil parameter.
When laser beam with alternating circular polarization ($V = \pm|V|$, $|V| \le 1$) hits polarized (P) electron beam, the scattening asymmetry is

$$\frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \approx -\frac{3}{4}\frac{E\omega_0}{m_e^2}VP \approx 2\%. \tag{6}$$

TEM-wave depolarizer at VEPP-4M

Beam depolarizer is located at the injection area of VEPP-4M collider. It is a pair of conductive plates along the beamline, 800 mm length, 40 mm vertical gap. Electrical signals are applied to the ends of the plates to form vertically polarized standing TEM wave in the gap. These sinusoidal signals as long as RF cavity system are synchronized with atomic Rb clock with long-term stability of $\sim 10^{-10}$. Standard scan mode: frequency change speed is 1 keV/s (1.86 Hz/s), voltage in the gap is ~ 20 V. Frequency scanning range is chosen to cover energy uncertainty range and is 0.6 – 1 MeV.

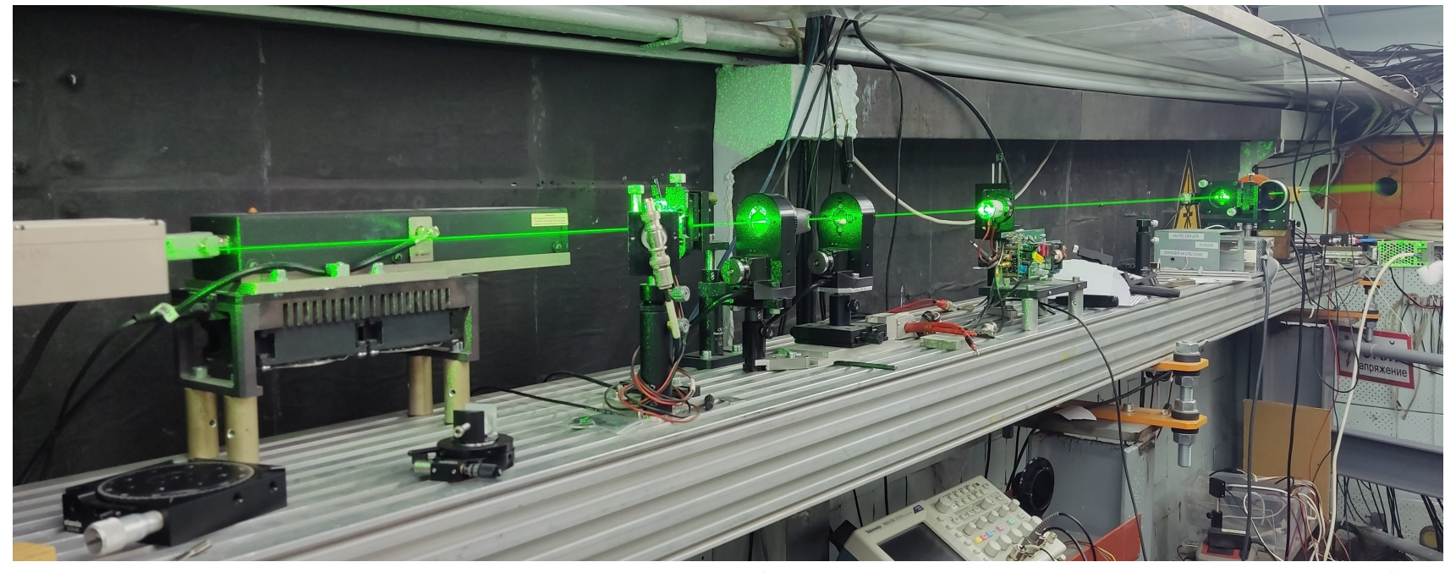
Laser polarimeter at VEPP-4M



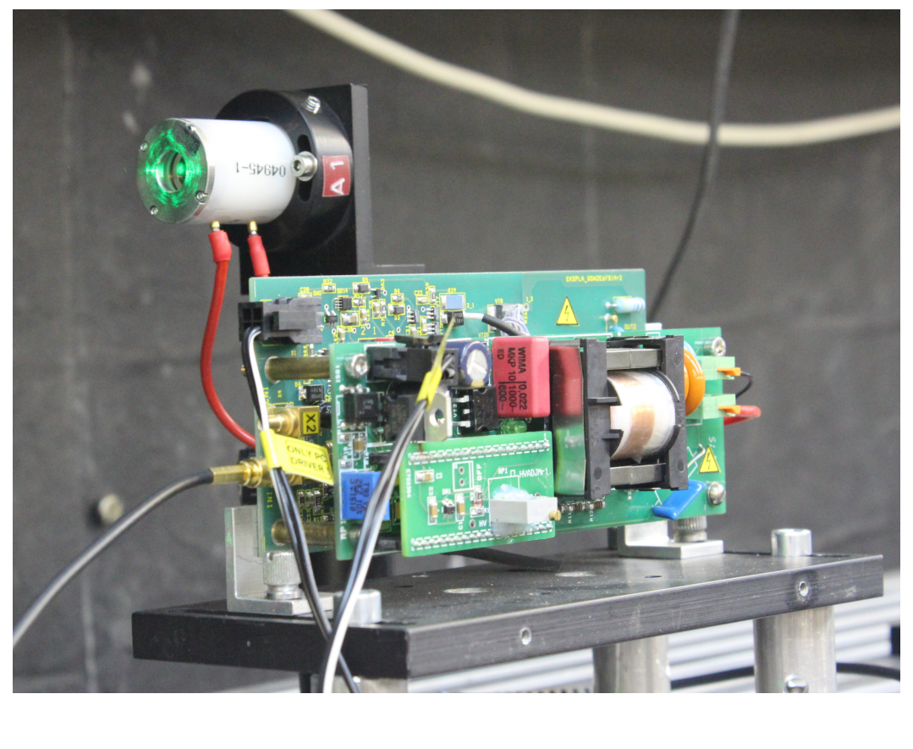
* GEM = gas electron multiplier; PP = $\lambda/4$ phase plate; PC = Pockels cell; LM⁻ = luminosity monitor; TS = tagging system for scattered electrons; BGO⁻ = photon BGO detector for calibration of tagging system; NEM = bending magnets; NEL, SEL = final focus quadrupole lenses.

Optical system

Optical bench ①



Pockels cell and driver ②

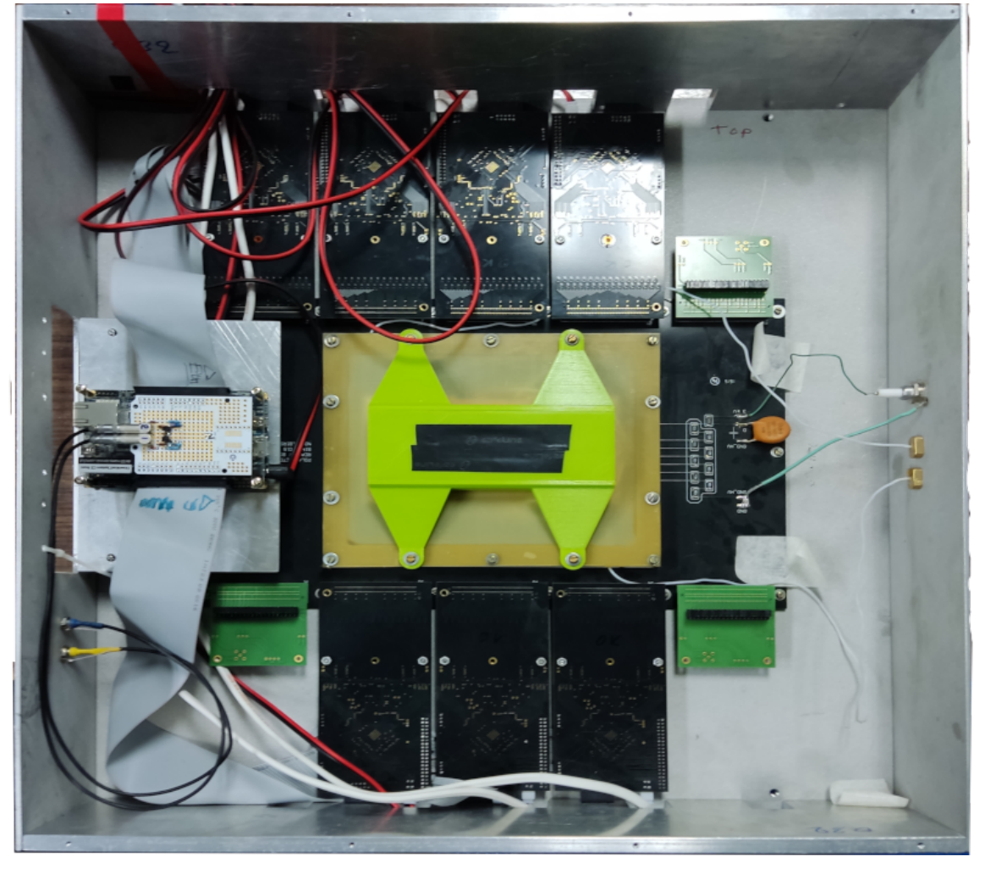


Movable mirror ③

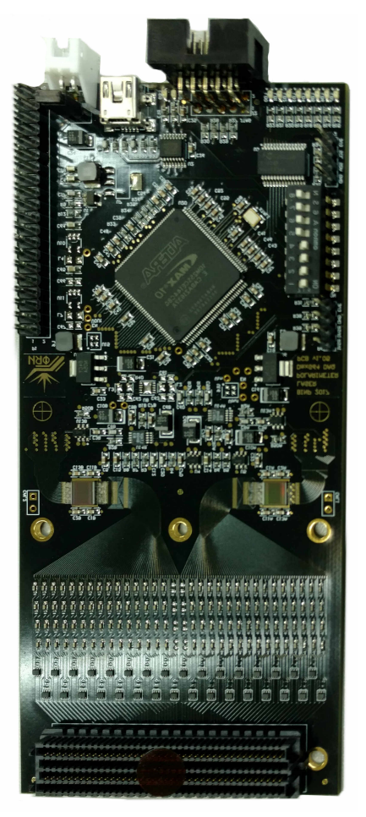
Linear laser beam polarization is transformed to circular one by a $\lambda/4$ phase plate. Left and right circular polarization are switched using a KD*P Pockels cell. Half-wave voltage is 3 kV. Switching can be regular: n left pulses, n right pulses, where $n = 1 - 16$, or pseudo-random based on a linear feedback shift register (LFSR). Laser beam is focused by a motorized collimator and then transported towards the electron beam via motorized 2-axis mirror and immovable water-cooled mirror in a vacuum chamber. The interaction region is located near final focus quadrupole lenses where the electron vertical angle spread is minimal.

Coordinate photon detector

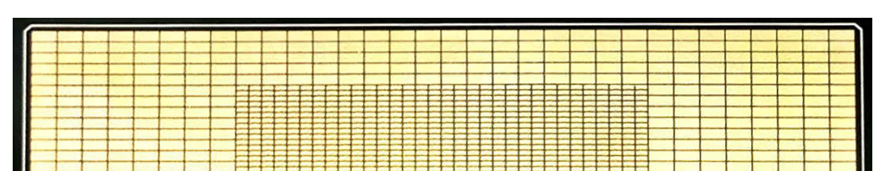
Detector view ④



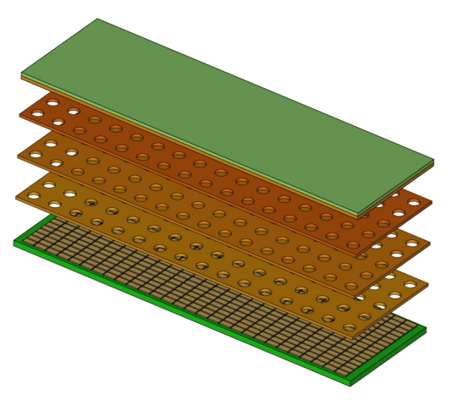
Readout board



Sensitive pads

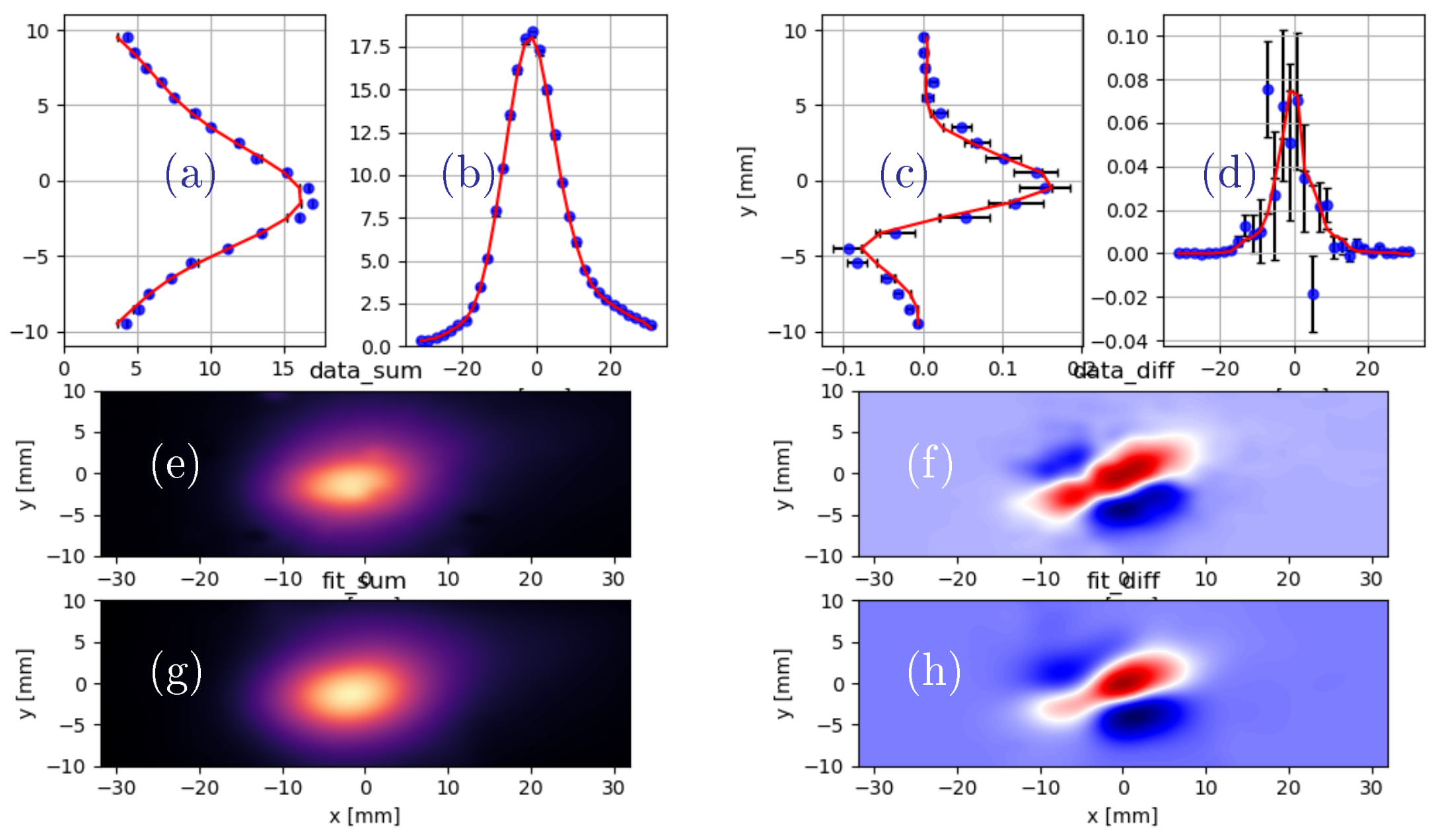


GEM scheme



Compton photons detector is based on 3-layer gas electron multiplier (GEM). Its sensitive area consist of 640 channels in the center and 512 channels on the periphery, totally 40 × 128 mm. Readout frequency providing reliable data-taking is 4 kHz, each Compton photon burst is sampled in 3 "frames".
The detector processing electronics is based on few analog/digital readout boards and system-on-chip with FPGA and ARM processor which serialize data and send it via Ethernet.
Typical Compton photon rates are 30 – 50 kHz at electron beam currents from 5 to 10 mA.

Data processing



(e): experimental sum $(D^L + D^R)(x,y)$
(f): experimental difference $(D^L - D^R)(x,y)$
(g): model sum $[B \otimes (C^L + C^R)](x,y)$
(h): model difference $[B \otimes (C^L - C^R)](x,y)$
(a): vertical projection of (e), (g)
(b): horizontal projection of (e), (g)
(c): vertical projection of (f), (h)
(d): horizontal projection of (f), (h)

The model of experimental gamma distributions $D^{L,R}(x,y)$ ("data") for left (L) and right (R) laser polarizations is the following:

$$D^{L,R}(x,y) = \frac{dN^{L,R}(x,y)}{dx\,dy} = \int \tilde{B}(x,y,\theta'_x,\theta'_y)\,C^{L,R}(\theta'_x,\theta'_y)d\theta'_x\,d\theta'_y \approx \int B(x-x',y-y')\,C^{L,R}\left(\frac{x'}{L},\frac{y'}{L}\right)\frac{dx'\,dy'}{L^2} = B(x,y)\otimes C^{L,R}(x,y)\,, \tag{7}$$

where "⊗" denotes a convolution and $C^{L,R}(\theta'_x,\theta'_y)$ is theoretical gamma distributions ("Compton") for left and right laser polarizations; $B(x,y,\theta'_x,\theta'_y)$ is a function representing distortion of Compton photons distribution due to the electron beam and scattering at materials ("beam"). Let introduce Fourier images ($\mathcal{F}$):

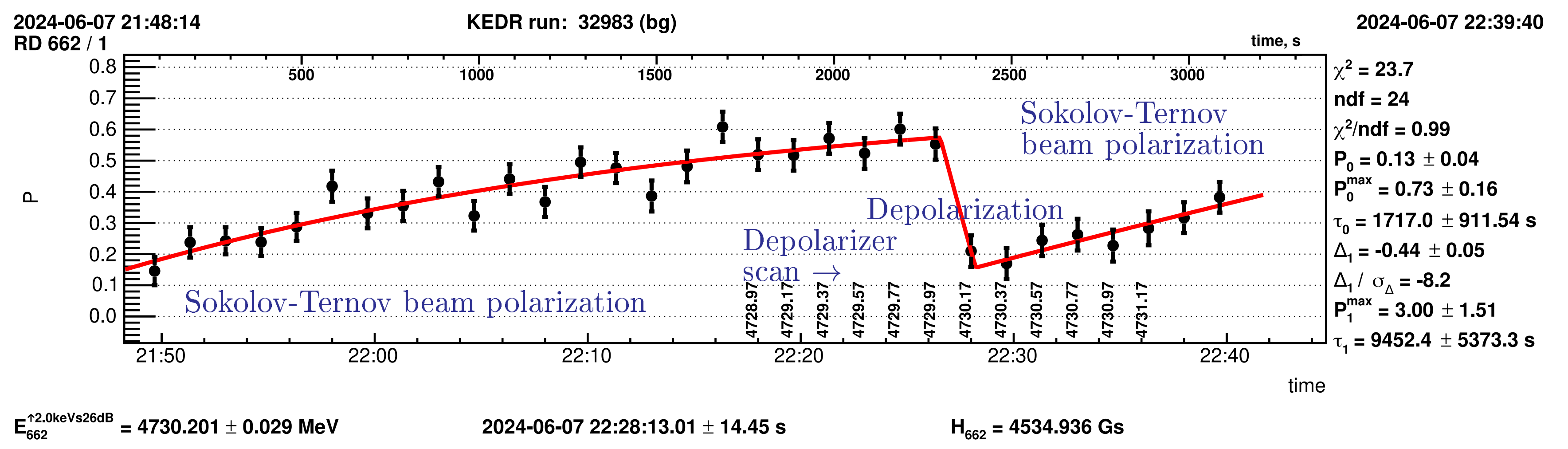
$$\hat{D} = \mathcal{F}\left[\frac{D^L}{N_L} + \frac{D^R}{N_R}\right], \quad \hat{C} = \mathcal{F}\left[C^L + C^R\right]. \tag{8}$$

Using properties of convolution,

$$B^*(x,y) = \mathcal{F}^{-1}\left(\frac{\hat{D}}{\hat{C}+\delta}\cdot\underbrace{\frac{|\hat{C}|^2}{|\hat{C}|^2 + k\Sigma|\hat{C}|^2}}_{\text{Wiener regularization}}\right), \tag{9}$$

where $\mathcal{F}^{-1}$ denotes an inverse $\delta \approx 10^{-12}$ suppresses zeros in denominator, and Wiener regularization with $k \approx 10^{-5}$ suppresses noise. This deconvolution is done over extended area of experimental data: $(32 \times 20) \to (96 \times 60)$ to suppress edge effects.
Then experimental distribution $D^L/N_L - D^L/N_L$ is fitted by function $B^* \otimes (C^L - C^R)$ with free parameters P, Q, β, while k, L, E, δ are fixed parameters, and V is calculated from Q. That is how the electron beam polarization P is calculated.

Depolarization example

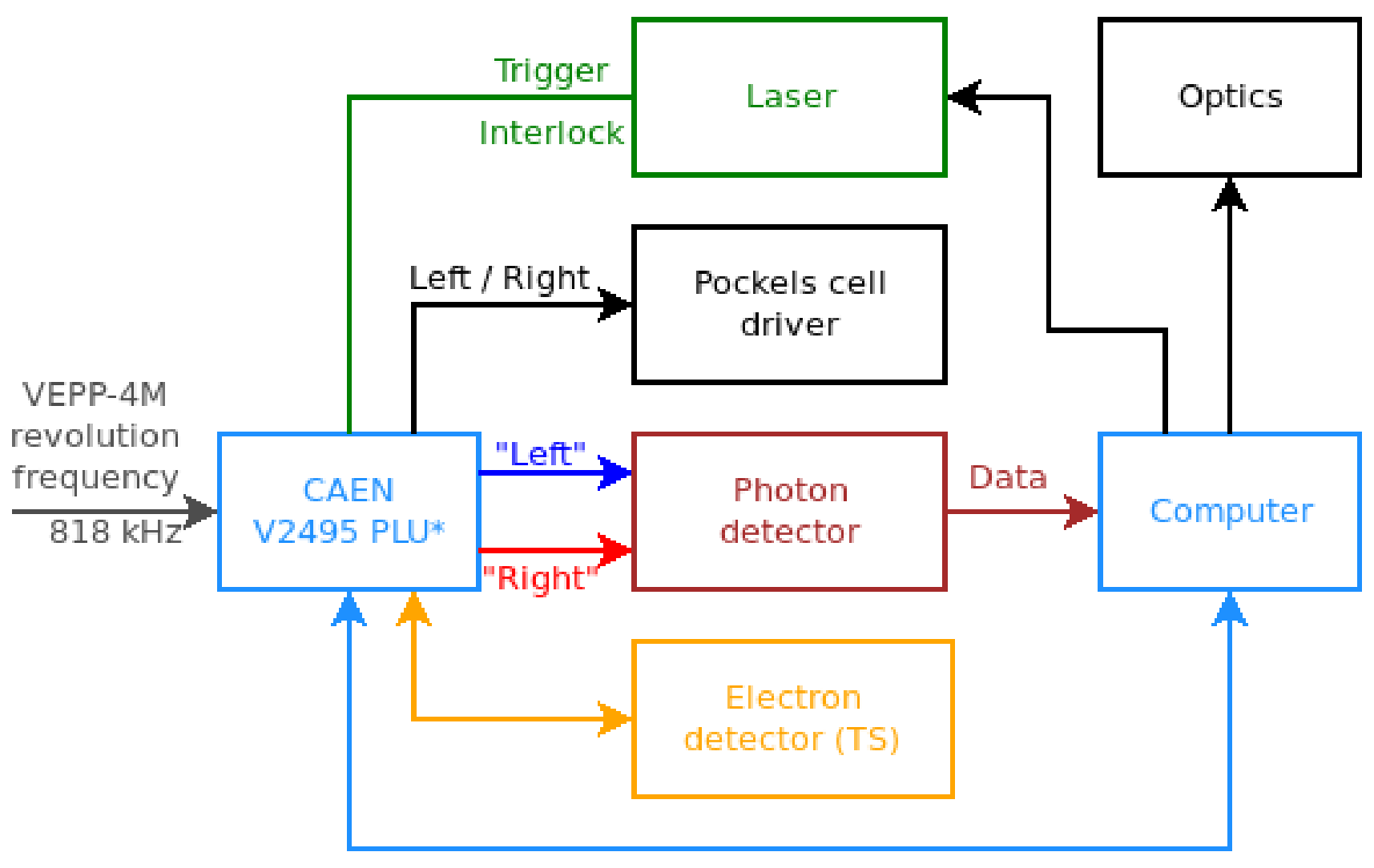


Laser

TECH-527 Advanced by Laser-Export. Co. Ltd.: pulsed Nd:YLF DPSS laser with acousto-optic modulator

Wavelength	527 nm
Pulse repetition rate	≤4 kHz
Average power	0.6 W
Pulse duration	5 ns (1.5 m)
Pulse instability	2 ns
Polarization	linear, vertical

Control system



* PLU = programmable logical unit; TS = tagging system

Control system provides two types of interaction with devices:
Fast signal control system is based on CAEN V2495 programmable logical unit (PLU) in VME standard. It has user-programmable FPGA chip, delay lines and input/output TTL/NIM ports. It takes VEPP-4M beam revolution frequency 818 kHz ("beam phase"), divides it by 204 so that 4014 Hz signal is generated it is the base frequency of the system. Laser is triggered with 214 µs signal with trailing edge synchronized with "beam phase" signal (jitter <2 ns). Triggering signal is delayed by inner digital delay line and external cable delay line with 1.33 ns step. The base signal triggers Pockels cell, coordinate gamma detector with its' suitable signal shape. Also the base signal is used as a gate to measure Compton rate by recoil electrons in tagging system.
Slow signal control system operates with movable optical devices: 2-axis mirror, motorized collimator, $\lambda/4$ phase plate. All these devices are drived via step motor controllers with RS-485 interface. A personal computer controls all the optical system including PLU and related hardware.
Also gamma detector data come to a similar PC and processed here.

Beam energy measurement procedure

1. Beam preparation (~ 45 minutes): reset of previous beams, magnetization cycle in VEPP-4; accumulation and acceleration of electrons in VEPP-3 (booster), injection in VEPP-4, then the same for positrons; acceleration of both beams from 1.9 GeV to 4.7 GeV.
2. Relaxation of guiding magnetic field and radiation polarization (~ 45 minutes). Beams does not collide due to electrostatic separation.
3. Beam convergence and data collection (~ 2 hours) by the KEDR detector with simultaneous energy calibrations. Up to 4 calibrations per KEDR run with alternating scanning directions can be performed.

Current status

- The "Laser Polarimeter" facility has been created, allowing calibration of the VEPP-4M beam energy with an accuracy of $\sim 3 \cdot 10^{-6}$ (15 keV) for the experiment on precision measurement of the $\Upsilon(1S)$ meson mass with the KEDR detector.
- Polarization measurement accuracy is 5 % in 50 seconds.
- The facility allows simultaneous energy calibration and data acquisition by KEDR detector.
- Full automation of the polarization measurement process is almost complete.

References

[1] *A.G. Shamov, O.L. Rezanova* "Revision of results on $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ masses", Physics Letters B, V 839, P 137766, 2023, `DOI:10.1016/j.physletb.2023.137766`

[2] *V.E. Blinov, et al.* "Status of laser polarimeter at VEPP-4M", Journal of Instrumentation, V 15, C08024, 2020, `DOI:10.1088/1748-0221/15/08/c08024`

[3] *V.V. Kaminskiy, et al.* "The GEM-based detector for tracking the Compton-scattered photons in the Laser Polarimeter facility at VEPP4-M collider", Journal of Instrumentation, V 15, C08019, 2020, `DOI:10.1088/1748-0221/15/08/C08019`