ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ СО АН СССР

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COLLIDING BEAM POLARIZATION MEASUREMENT USING SUPERCONDUCTING HELICAL UNDULATOR AT THE VEPP-2M STORAGE RING

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НОВОСИБИРСК

COLLIDING BEAM POLARIZATION MEASUREMENT USING SUPERCONDUCTING HELICAL UNDULATOR AT THE VEPP-2M STORAGE RING

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ABSTRACT

Compton scattering of circular polarized photons,as was shown at different storage rings [1-3], is an effective and sensitive method for the beam polarization measurement. The application of the synchrotron and undulator radiations [4,5] enlarges the possibilities of this method. This report presents the results of the calculation and measurements of the electron-positron colliding beam polarization at the VEPP-2M using the helical undulator installed in the interaction region as a source of circular polarized photons.

IDEA OF THE METHOD

The intense flux of circularly polarized photons emitted by electron passing through the helical undulator can be used for measurements of the positron beam polarization and vice versa.

Briefly remind about the properties of the undulator radiation. The average power in the dipole approximation is described by the equation:

$$W = \frac{2}{3} r_e^2 H_\perp^2 \gamma^2 N_e f_o e \quad , \qquad (1)$$

where $H_\perp$ is the amplitude value of the magnetic field on the undulator longitudinal axis, N_e is the number of the electrons (positrons) in the beam, f_o is a revolution frequency of the beam in the storage ring, l is the length of the undulator, r_e is the classical radius and γ is the relativistic factor of the electron. The photon energy in the undulator radiation is related to the radiation angle $n = \gamma \cdot \theta$ by the equation:

$$\omega_1 = \frac{2\,\gamma^2 \omega_o}{1+K^2+n^2} \quad , \qquad (2)$$

where $\omega_o = \frac{2\pi hc}{\lambda_o}$, λ_o is the length of the magnetic field period of the undulator, c is the speed of light, m_o is the electron rest mass, h is the Plank constant reduced and K is the undulator parameter, which is given by the equation:

$$K = \frac{e \cdot H_\perp \cdot \lambda_o}{2\pi \cdot m_o \cdot c^2} \quad , \qquad (3)$$

where e is the electron charge magnitude.

The degree of the circular polarization ξ_2 of the photons generated by the helical undulator is of about 100 % near $n \approx 0$ when $\omega_1 = \omega_{1max} = \frac{2\gamma^2\omega_o}{1+K^2}$. Using the helical undulator as a generator of photons, the number of the Compton scatterings per second can be written as:

$$\dot{N} = \frac{N_e}{S}\int_0^\infty \sigma\cdot\left(\frac{dN^+}{d\omega} + \frac{dN^-}{d\omega}\right)\cdot d\omega\ , \qquad (4)$$

where $dN^{\pm}/d\omega$ is the photon spectrum current density with the positive and negative helicity, S is the effective cross section of the beams in the interaction region.

The Compton scattering cross-section σ for the photon energy ω_1 in the head-on-collision with the ultrarelativistic electron (positron), with transverse polarization $\zeta_\perp$, is given by the expressions [6]:

$$d\sigma = d\sigma_o + \xi_2\cdot\zeta_\perp\cdot d\sigma_\perp\ , \qquad (5)$$

$$d\sigma_o = 4\cdot r_e^2\cdot\frac{[2\cdot\chi^2(1+n^2)+(1+n^2+2\cdot\chi)\cdot(1+n^4)]\cdot n\cdot dn\cdot d\varphi}{(1+n^2)^2\cdot(1+n^2+2\cdot\chi)^3}\ , \qquad (6)$$

$$d\sigma_\perp = 8\cdot r_e^2\cdot\frac{\chi\cdot n^2\cdot dn\cdot\sin\varphi\cdot d\varphi}{(1+n^2)\cdot(1+n^2+2\cdot\chi)^3}\ , \qquad (7)$$

where $\chi = 2\cdot\gamma\cdot\omega_1/m_oc^2$ is the photon energy in the electron rest frame, θ and φ are the polar and azimuthal angles of the secondary gamma quanta momenta in the laboratory system.

The angular asymmetry of the secondary gamma quanta emission is characterized by the parameter $A = d\sigma_\perp/d\sigma_o$ and reaches the maximum $A = 0.3$ when $\chi \approx 1$ and $n \approx 1$.

For the storage ring VEPP-2M (the beam energy is E = 650 MeV) the maximum of the asymmetry can be achieved when $h\omega_1 = 200$ eV, that corresponds to the undulator magnetic field period $\lambda_o = 2.5$ cm. The energy of the secondary gamma quanta ω_2 determined by the equation

$$\omega_2 = 4\cdot\gamma^2\cdot\omega_1\cdot(1+n^2+2\cdot\chi) \qquad (8)$$

can reach $\omega_{2max} = 400$ Mev.

In the case of the undulator usage the calculation of the average asymmetry <A> must take into account the total spectrum and both helicitics of the undulator radiation:

$$\langle A\rangle = \frac{\int_0^\infty \left(\frac{dN^+}{d\omega} - \frac{dN^-}{d\omega}\right)\cdot d\sigma_\perp\cdot d\omega}{\int_0^\infty \left(\frac{dN^+}{d\omega} + \frac{dN^-}{d\omega}\right)\cdot d\sigma_o\cdot d\omega}\ , \qquad (9)$$

where $d\sigma_\perp$ and $d\sigma_o$ are given by (6-7).

In the general case the expressions for the photon spectral density $dN^{\pm}/d\omega$ are too complicated [7,8], but for practically interesting values $K \le 1$, they can be simplified to the following:

$$\frac{dN^+}{d\omega} = \frac{\alpha}{\omega_o\lambda_o}\cdot K\left(\frac{\omega}{\omega_o}\right)^2\cdot N_e\cdot f_o\cdot l\ , \qquad (10)$$

$$\frac{dN^+}{d\omega} = \frac{\alpha}{\omega_o\lambda_o}\cdot K\cdot\left(1 - \left(\frac{\omega}{\omega_o}\right)^2\right)\cdot N_e\cdot f_o\cdot l\ , \qquad (11)$$

where $\alpha = e^2/h^2$ is the fine structure constant.

To optimize the undulator parameters for the storage ring VEPP-2M the value $\Delta = \langle A\cdot\dot{N}^{1/2}\rangle$ was calculated, that characterized the polarimeter sensitivity. The calculation of the counting rate $\dot{N}$ (eq. 3) was performed for the Gaussian density distribution of the particles in the beam and the real beam envelopes along the interaction area.

From the results of the calculation are shown in fig.1, one can see that for the undulator parameter K the region 0.5 < K < 1 (this corresponds to 2 kGs < $H_\perp$ < 4 kGs) is optimal. The asymmetry <A> = 12 % and $\dot{N} \approx 1.0$ kHz could be reached in the energy spectrum region $0.5\ \omega_{2max} < \omega_2 \le \omega_{2max} = 350$ MeV with the currents of the colliding electron and positron beams are equal to $I^+ x I^- = 6x6\ mA^2$ (this corresponds to $N_e^\pm = 2.5 \cdot 10^9$).

The background processes for the Compton scattering are the Bremsstrahlung on the residual gas atoms and single Bremsstrahlung in the electron-positron interaction [8].

A simple estimation shows that the admissible level of the background from the first process could be obtained with the vacuum 10^{-10}Torr. Background from the single Bremsstrahlung can be suppressed by the electrostatic separation of the electron and positron beams at the interaction point in vertical direction at the distance of a few beam sizes. In this case the luminosity of the colliding electron-positron beams $L_{e^+e^-}$ goes down by $10^2 \div 10^3$ times, but the decrease of the electron-photon luminosity is insignificant, because the photon "spot" in the interaction point is much larger than the electron beam vertical size $\sigma_z = 5 \cdot 10^{-4}$cm.

The behaviour of the electron-photon and the electron-positron luminosity as a function of the value of the electrostatic separation Δz are shown in fig.2. The contribution of the background Bremsstrahlung on the residual gas atoms is given by the dashed line.

THE UNDULATOR DESIGN

The analysis of the different undulator designs shown that the optimal parameters for polarization measurement can be obtained only with a superconducting coil. However, for the first study of the parasitic beam interaction with the helical magnetic field and especially with the edge fields, we have installed in the VEPP-2M storage ring the 25 cm long, room temperature undulator. The 2.5 cm period magnetic field of 1.3 kGs was provided by the double soft iron helix and intense water cooled double copper helix with 5 kA DC current.

We found that the particle closed orbit distortions from this undulator are easily compensated and the betatron turn shifts are negligible.

The effect of the backward Compton scattering of the undulator photons on the colliding electron-positron beams has been firstly observed in 1980 [9]. We have measured the counting rate of the Compton scattered photons $\dot{N} \approx 200$ Hz (approximately two times less than the calculated value). The experimental measurements of the radiation polarization for the colliding beams with a "warm" undulator were rather difficult due to the unstable background conditions from the additional vacuum chamber heat by the extremely high current density in the undulator copper bars (85 A/mm^2) and were not performed.

This "warm" undulator was used for the measurements of gamma ray spectra and helicity that were found in good agreement with theoretical predictions [10]*.

The design of the superconducting helical undulator is based on the same approach as the conventional one with the additional "self-compensating" conditions: $\int H_{x,z} \cdot dl = 0$. Under these conditions there are no a particle orbit perturbations outside of the insertion device. The undulator magnet was divided into two equal parts placed around the interaction point with a gap $1.5 \cdot \lambda_o$. Each part consists of four helix periods. The superconducting coil from NbTi cable (⌀ 0.07 cm) was winded inside the double soft iron helix (fig.3). To improve the cooling conditions the iron and the support copper tube are under the liquid helium temperature. The thin stainless still vacuum chamber with aperture 1.8 cm contacts also on the liquid helium and works as the cryogenic pump in the storage ring straight section.

The main parameters of the superconducting undulator installed in the storage ring VEPP-2M are shown in Table 1.

Details of the design and the magnetic field calculations are given elsewhere [12].

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*The experiments with soft X-ray golography were carried out using this undulator in 1981-83 [11].

Table 1. Parameters of the superconducting helical undulator installed in the storage ring VEPP-2M.

The maximum value of the magnetic field at the beam axis, kGs	4.70
The number of the magnetic field periods	8
Lenght of the magnetic field period, cm	2.4
The critical value of the curent in the coil, A	430
The total length of the area with the helical field, cm	20
Aperture of the vacuum chamber, cm	1.8
The cable diameter, cm	0.07
The outer diameter of the windings, cm	4.4
The inner diameter of the windings, cm	2.0
The number of the coils at a single period of the magnetic field	308
The ramping time, s	1
The liquid helium consumption, litres per hour	1.5

The measurement of the magnetic field on the longitudinal axis of the undulator was performed by the Hall probe working at the liquid helium temperature in the immersed cryostate. The experimental (solid line) and calculated (dashed line) dependencies of the magnetic field amplitude on the axis as a function of the current in the coil are shown in fig.4. The measurement shows the complete absence of the magnet training effect.

The distributions of the H_x and H_z components of the magnetic field on the undulator axis measured by the Hall probe when the current in the windings was equal to 200 A are plotted in fig.5.

The calculated orbit displacement inside this helical undulator is shown in fig.6. One can see that the "self-compensation" scheme works with a good precision.

In 1984 the superconducting undulator was installed in one of the straight sections of the VEPP-2M storage ring. Its turning on shows the practical absence of the closed orbit distortion. The measured betatron tune shift was equal to $\Delta\nu_{xz} \approx 10^{-3}$.

THE EXPERIMENT DESCRIPTION

The scheme of the experiment [13] at the storage ring VEPP-2M is shown in fig.7. The superconducting helical undulator was installed in the center of the straight section. On each side of the interaction point at 6 m from it two detectors are placed which consist of plastic (polistirol) scintillator counters with the dimensions of $1\times0.5\times4$ cm^3 remotedly controlled (positioning accuracy of about 10^{-2} cm) to measure the "up-down" asymmetry, the inductive proportional chambers to measure the gamma quanta coordinate distributions (with the spatial resolution of about $\approx$ 200 μm), and the total absorption calorimeter (20 radiation lengths) based on NaI (Tl) crystal. Prior to the scintillator counters the converter (two radiation lengths of lead) is placed providing a detection efficiency of about 35 %. The efficiency measurements and the energy calibration of the detectors were performed by using the single Bremsstrahlung of the electron-positron interaction.

To improve the vacuum conditions the straight section was equipped by two ion-getter pumps. During the experiment vacuum $(1\cdot10^{-9}-\ 6\cdot10^{-10})$ Torr. was measured by the counting rate of the gamma quanta from Bremsstrahlung.

Besides that, the coils generating the longitudinal RF magnetic field were mounted in same straight section. This device called "Flipper" can adiabatically reverse the electron (positron) spins without reduction of the beam polarization degree [14]. The same device but with a small RF power supply and noise frequency modulation, can be used for the fast beam depolarization due to a multicrossing of the spin resonance.

The coordinate distributions of the gamma quanta measured by the proportional chambers are shown in fig.8. One can see the distributions of the background quanta from the Bremsstrahlung on the residual gas atoms (fig.8(A)) without the undulator field and turned on the electrostatic separation system (vertical separation at the interaction point was equal to $\Delta z \geq 2\cdot\sigma_{zo} = 10^{-3}$cm). The width of the gamma quanta distributions on the half-maximum in this case are $\Sigma_x = 2.5$ cm, $\Sigma_z = 1.6$ cm. The background photon counting rate was 400 Hz at the currents of $I^+ \times I^- = 5\times5$ mA^2. The coordinate distributions under the same conditions are shown in fig.8(B) but the undulator field ($H_\perp = 3.75$ kGs, $K = 0.84$, $\omega_1 = 100$ MeV and $\omega_2 = 330$ MeV) and the electrostatic separation system were turned on. Two bumps in the X coordinate distribution correspond to the local trajectory distortions of the particles in the undulator (see fig.6). In this case the width at half-maximum of the X coordinate distribution central part becomes equal to Σ_x=1.8 cm. The control runs without the electrostatic separation demonstrated that the gamma quanta came from the interaction point. After that all experimental runs were done with the events selected only from the central part of the horizontal distribution. The Z coordinate distribution has the width at half-maximum equal to Σ_z= 1.1 cm under the same conditions. The decrease of the coordinate distribution widths is caused by the appearance of the Compton interaction.

The experimental energy spectrum of the Compton gamma quanta is shown in fig.9. The measured effect-to-background ratio was equal to 1.5. The Compton gamma quanta counting rate was $\dot{N}_{exp}$= 600 Hz and this value was slightly less than the expected one $\dot{N}_{acc} \approx$ 750 Hz.

The background from Bremsstrahlung on the residual gas atoms in spite of the all undertaken efforts was still too high. The spectrum in the energy range $0.25 < \omega_2/E < 0.63$ (fig.9) was separated by the electronics for the polarization measurements.

The colliding beam polarization degree was measured at the energy of 650 MeV, where the radiation polarization time is $\tau_p \approx$ 1 hour. The beams were polarized at the coupling resonance (the life time of the beams of about 3 hours). After the time of $\tau = 2\cdot\tau_p$ when the polarization degree reached $\xi_\perp$= 0.8 (the currents of the colliding beams were $I^+ \times I^-$= 5x5 mA^2) tunes

were changed to the working point (ν_x= 3.078 and ν_z= 3.106), the electrostastical separation system and the undulator magnetic field were switched on and the data taking started.

The measured value of the "up-down" asymmetry was determined from the equation:

$$A_{exp} = \frac{N_U - N_D}{N_U + N_D}$$

where N_U and N_D are the number of events in the upper and lower scintillating counters in the selected energy range. The data taking time in each point was equal to 45 s. After 300-400 s of measuring the "up-down" asymmetry, the RF depolarizer was switched on and the resonance depolarization was observed (fig.10.). Such procedure gives a possibility for the absolute measurement of the asymmetry.We obtained for the electron beam ΔA^-_{exp}= (7.3 ± 0.8) % and ΔA^+_{exp}= (7.1 ± 0.8) % for the positron beam.The calculated value was equal to ΔA_{cal}= (10.5 ± 1.0) % at the same conditions. Taking into account the presence of the background, the measured polarization degree is evaluated by the equation:

$$\zeta_{\perp exp} = \zeta_0 \cdot \frac{\Delta A_{exp}}{\Delta A_{cal}} \cdot \frac{N_{eff} + N_{background}}{N_{eff}}$$

and amounts to:

$$\zeta^-_{\perp exp} \approx \zeta^+_{\perp exp} = 0.83 \pm 0.07 \pm 0.08$$

Here the first error is experimental (statistical) and the second is the expected error of the polarization degree (calculation).

The measured behaviour of the asymmetry in the other experimental run is shown in fig.11 when an adiabatic reversal of the particle spine at the points "a", "b" and "c" was performed with the help of the "Flipper". At the point "a"the particles spins were 180° reversed with respect to the "natural" direction, at the point "b" the polarization was restored (both its value and direction) and at the point "c" the next spin-flip occurred. At the point "d" the beams were depolarized. Thus fig.11 demonstrates a good sensitivity of the undulator polarimeter to the reversal of the electron (positron) beam polarization direction.

CONCLUSIONS

Summarizing the results of the performed experiments we can conclude that a new technique of the colliding beam polarization measurement using the helical undulator provides under the conditions of the storage ring VEPP-2M a 10 per cent accuracy in the polarization degree measurement during a 45 s. run and also enables the determination of the polarization direction of the colliding beams.

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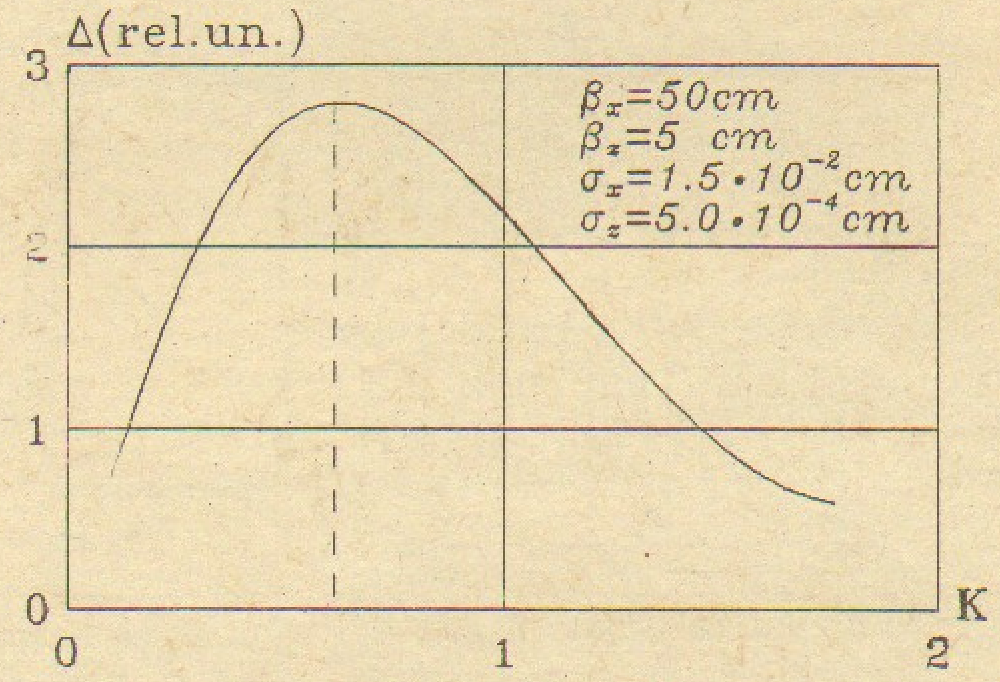

Fig.1 Dependence of the undulator polarimeter sensitivity $\Delta = \langle A\cdot\dot{N}^{1/2}\rangle$ on the undulator parameter K.

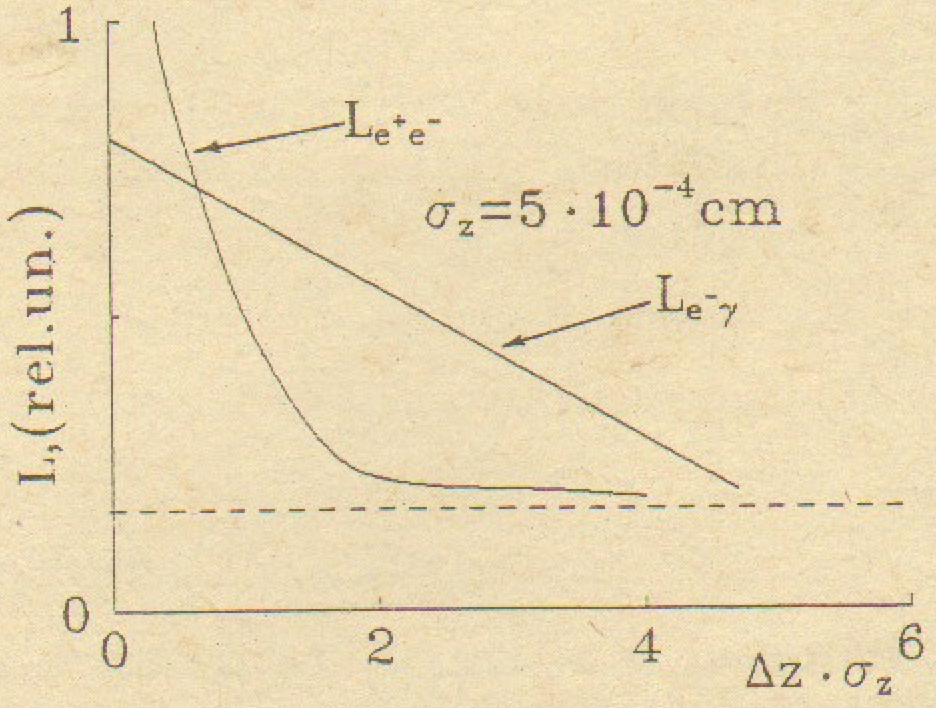

Fig.2 The dependence of the electron-positron and electron-photon luminosity on vertical electrostatic beam separation in the interaction point.

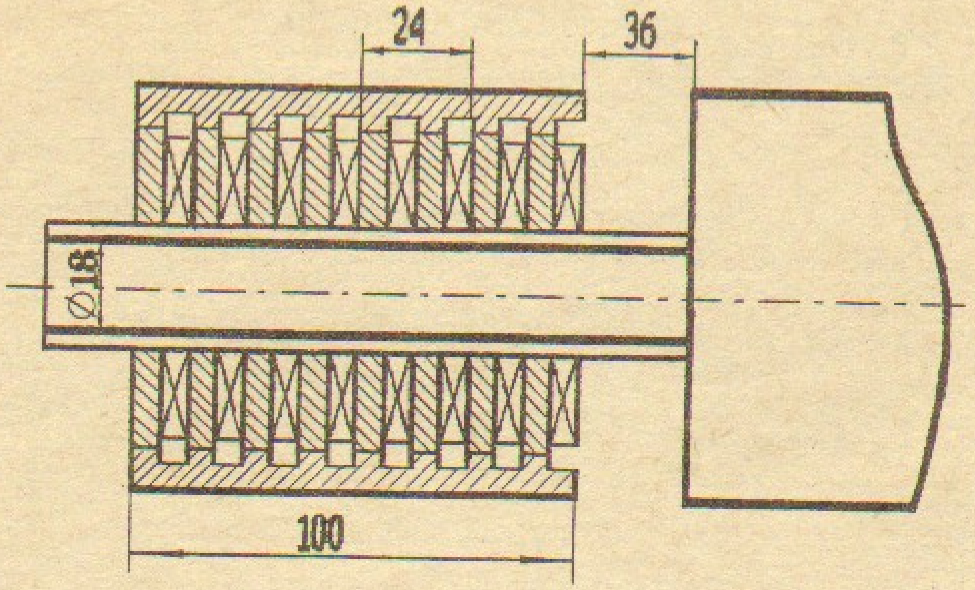

Fig.3 The undulator magnet design.All dimensions in mm.

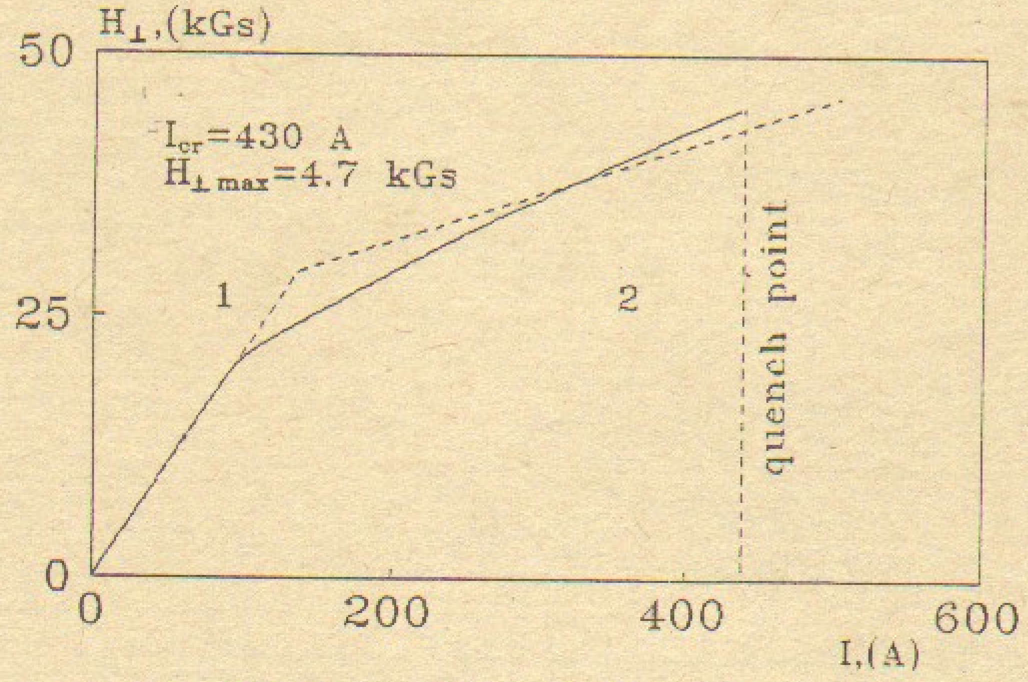

Fig.4 The magnetic field amplitude on the axis vs. the coil current. 1 is the calculation, 2 is the experimental curve.

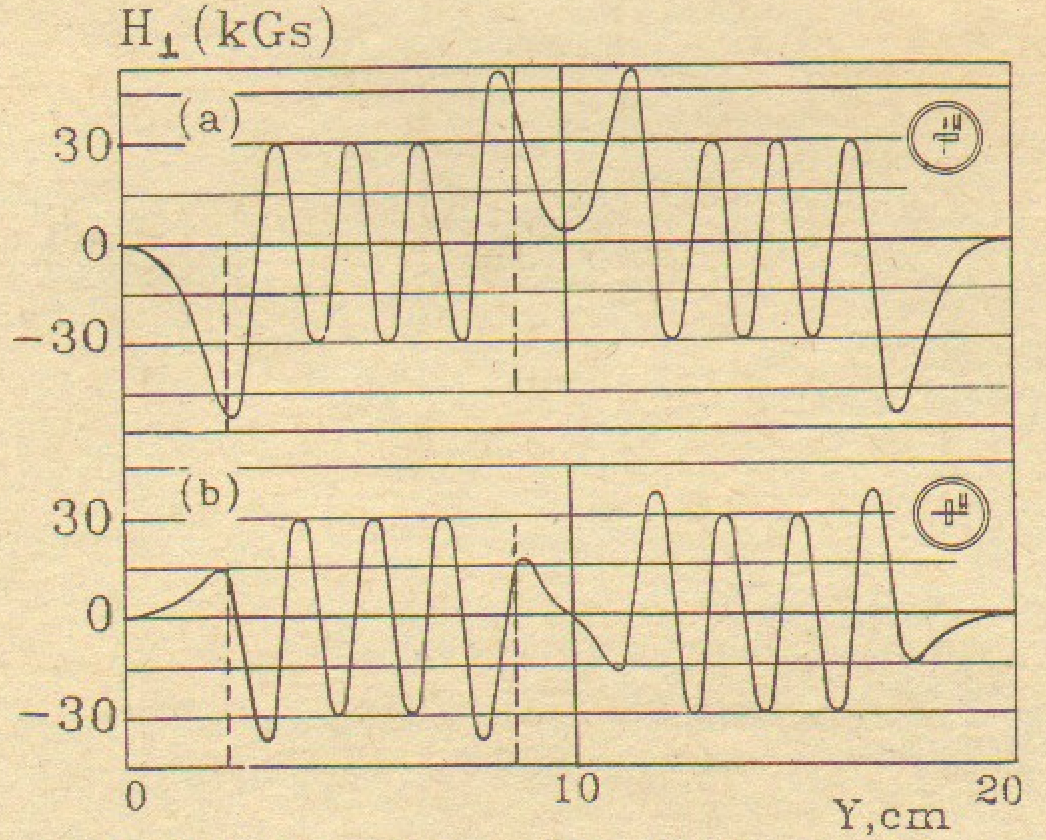

Fig.5 The magnetic fieldcomponent distribution. a is H_x component and b is H_z component on undulator axis. The coil current is 200 A.

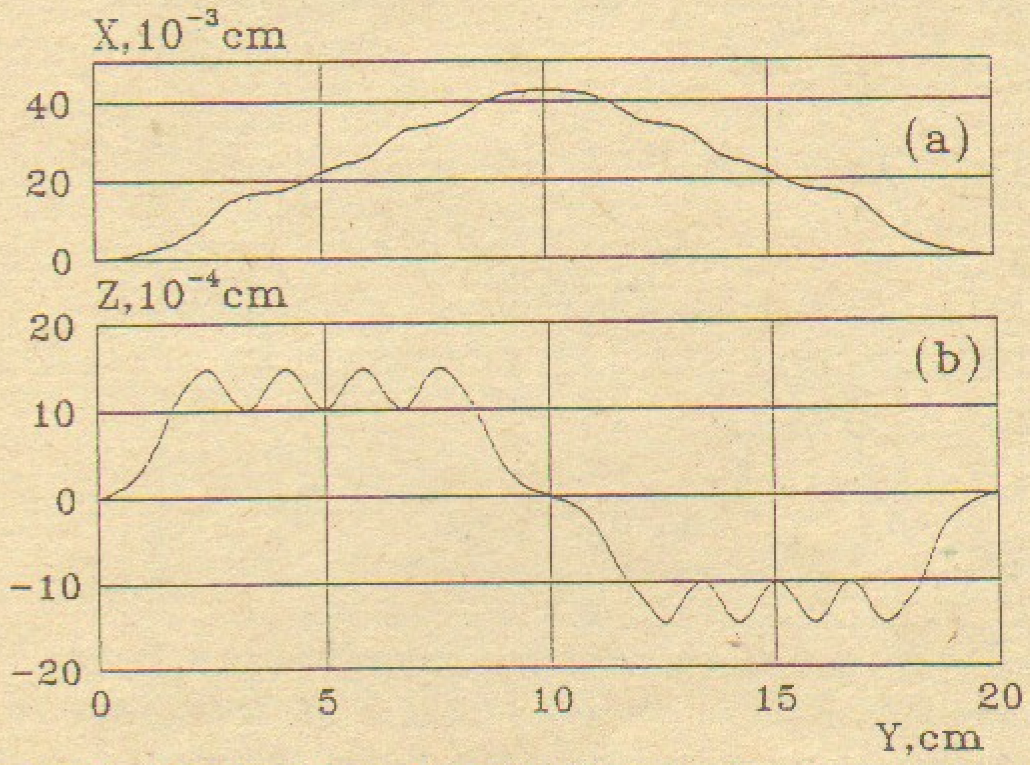

Fig.6 The closed orbit displacement in the undulator. (a) is the X coordinate (horisontal), (b) is the Z coordinate (vertical).

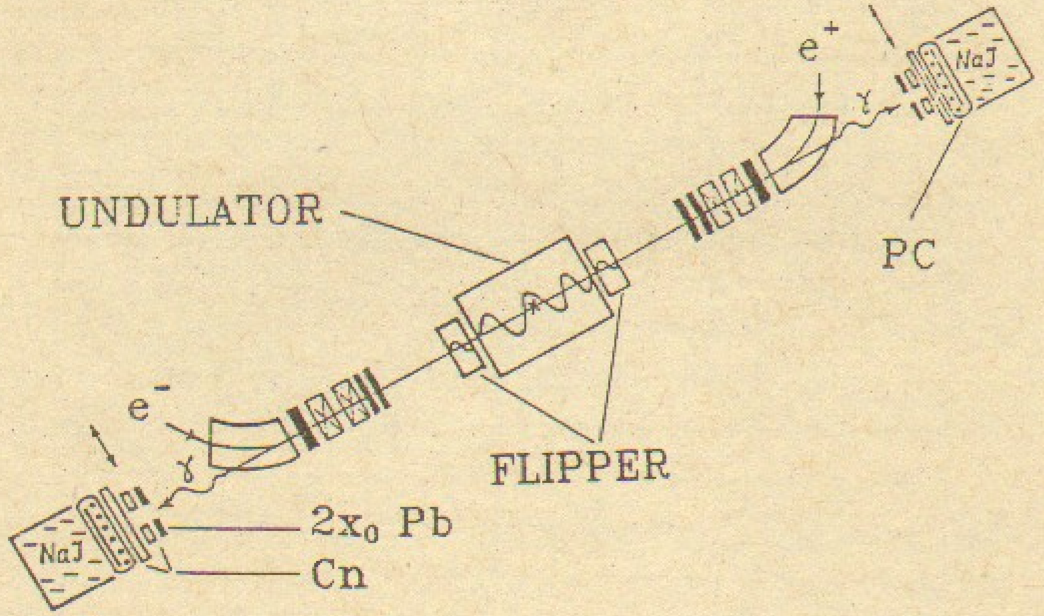

Fig.7 The scheme of the experiment at the storage ring VEPP-2M.

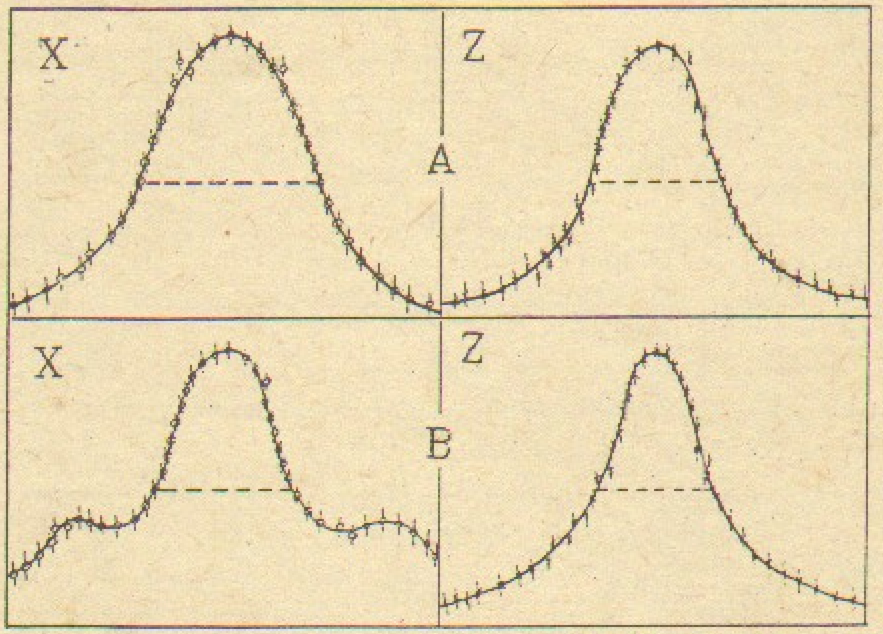

Fig.8 The gamma quanta coordinate distributions. A is the distribution of background of the gamma quanta due to Bremsstrahlung on residual gas atoms. The undulator is off. B is the distributions of the gamma quanta with the undulator field on.

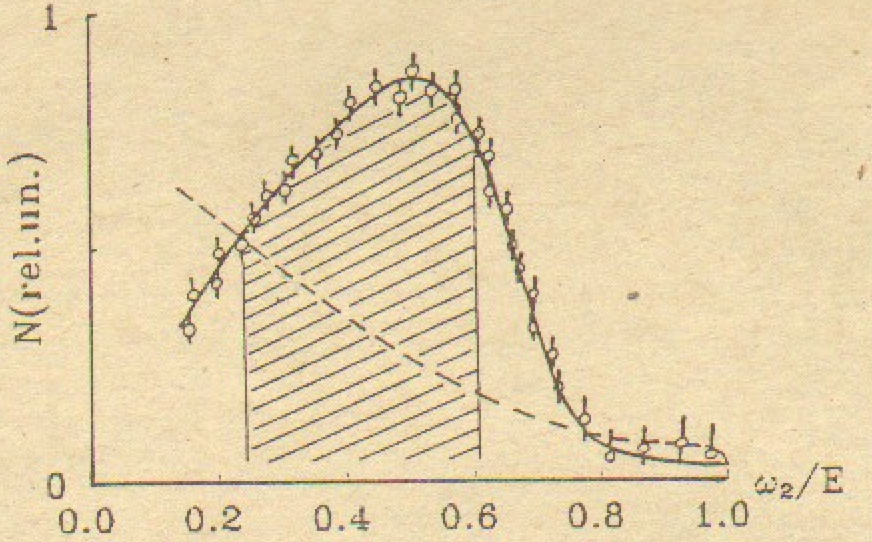

Fig.9 The experimental energy spectrum of the backscatted Compton gamma quanta.

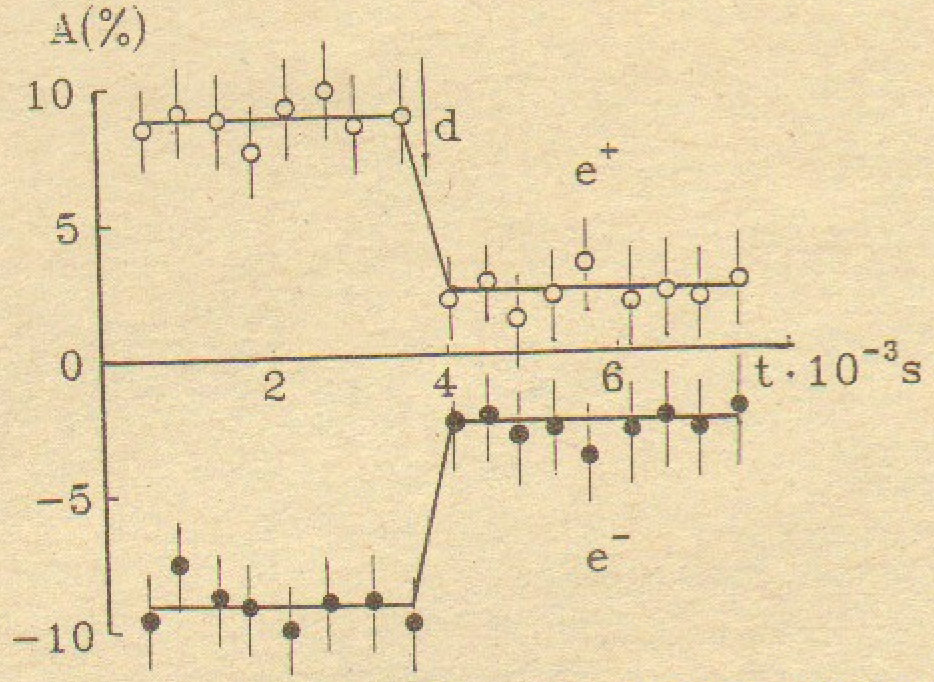

Fig.10 The resonance depolarization of the electron and positron beams.

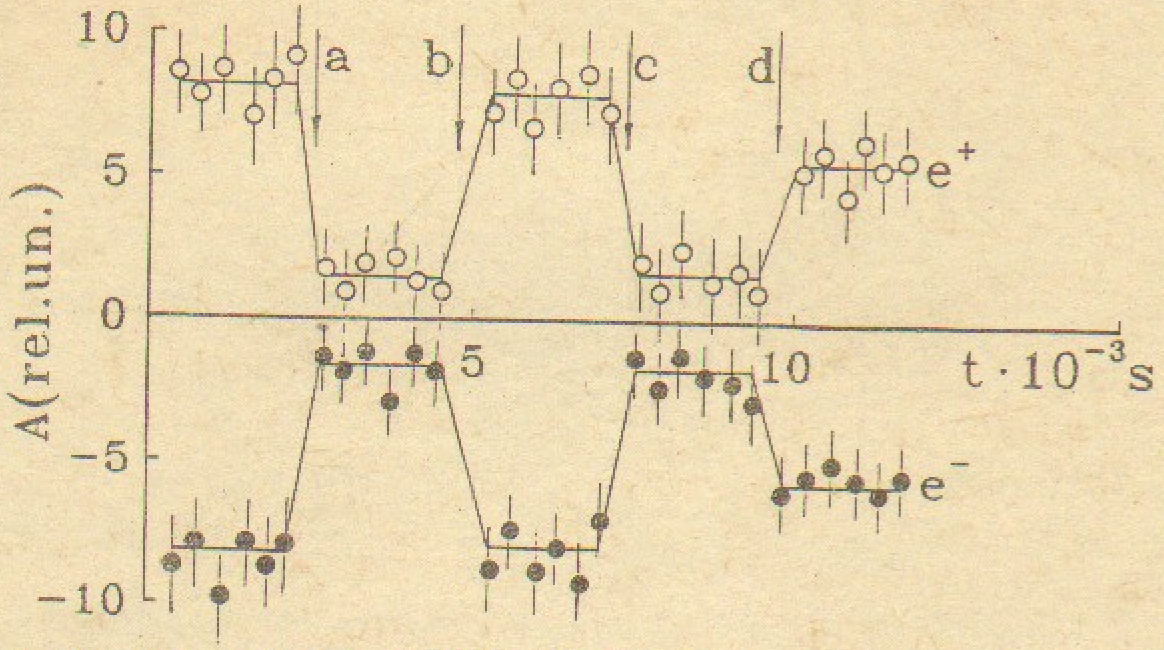

Fig.11 The asymmetry dependence on time. At the points a, b and c the adiabatic reversal of the particle spins was performed. At the point d the resonant depolarization occured.

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ИЗМЕРЕНИЕ ПОЛЯРИЗАЦИИ ВСТРЕЧНЫХ ПУЧКОВ НА НАКОПИТЕЛЕ ВЭПП-2М С ПОМОЩЬЮ СВЕРХПРОВОДЯЩЕГО СПИРАЛЬНОГО ОНДУЛЯТОРА

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