Plan for longitudinal polarization test at VEPP-4M

D.V. Dorokhova, E.B. Levichev and S.A. Nikitin

BINP SB RAS Novosibirsk

FTCF 2024 workshop
14-18 Nov 2024

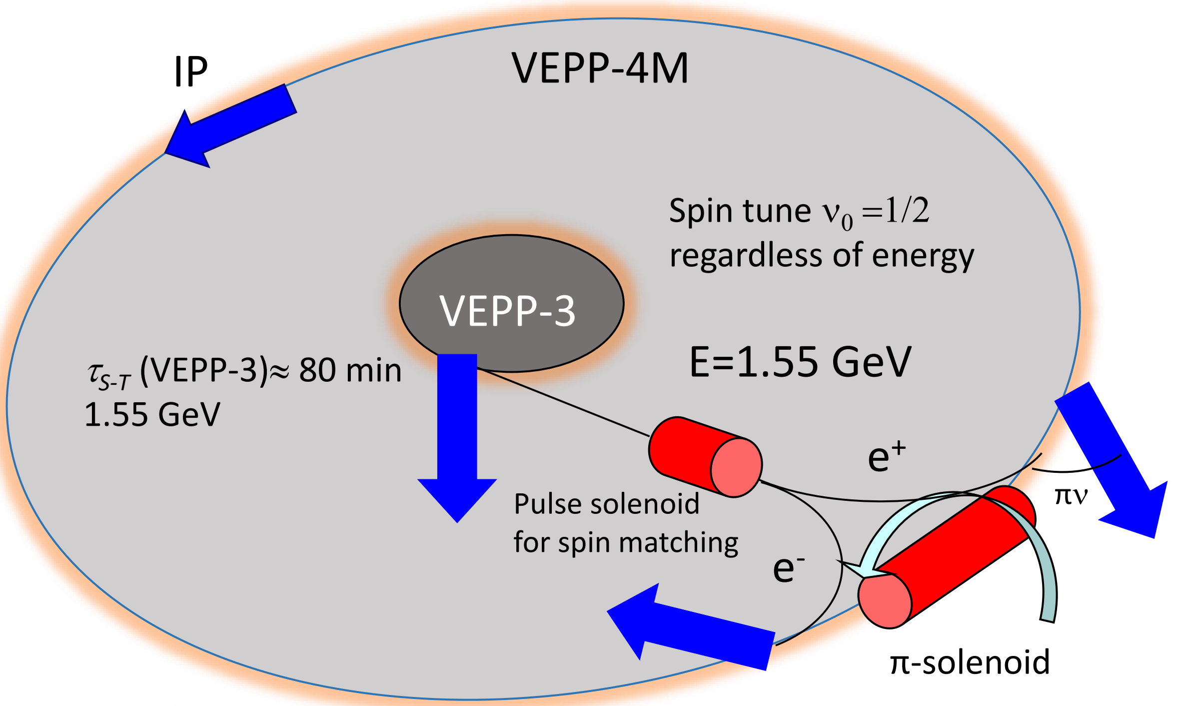
- Motivation
- Concept of Siberian Snake at VEPP-4M
- What to study
- Proposal on required polarization manipulation in injection beam-line VEPP-3-VEPP-4
- Structure of snake solenoid insert and its properties
- Matching VEPP-4M optics with Siberian Snake insert
- Our experience in spin manipulation in injection beam-line
- Special experiment with obtaining longitudinal polarization without upgrading VEPP-4M
- Minimum program

Motivation

- Longitudinal polarization in Super C-Tau is based on Siberian snakes
- The use of spin rotators based on SC solenoids is being considered to obtain longitudinal polarization in the CEPC super-collider project
- The effect of radiation on polarization makes spin rotators in lepton colliders more complex in relation to the properties of similar devices used to cross spin resonances in ring accelerators of heavy particles
- To date, only one example of the implementation of the “Siberian snake” on an electron storage ring is known - at energy of about 700 MeV on AmPS (Netherlands)
- The VEPP-4 complex has unique capabilities and gained experience in accelerator experiments with polarized beams (booster-polarizer VEPP-3, resonant depolarization technique, spin resonance intersections, partial Siberian snake, Touschek polarimeter, laser polarimeter in combination with a system of scattered electrons)
- Why not gain experience in creating and studying the properties of spin rotators in the form of solenoid on VEPP-4M for its use in future machines?

Siberian Snake to obtain longitudinal polarization at VEPP-4M

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



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:

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

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

Depolarization time at 1548 MeV: td=425 min
Po=75% , electron beam polarization degree at injection
<P>=Po*td/t*[1-exp(-t/td)]=66% average value for t=1.5 h

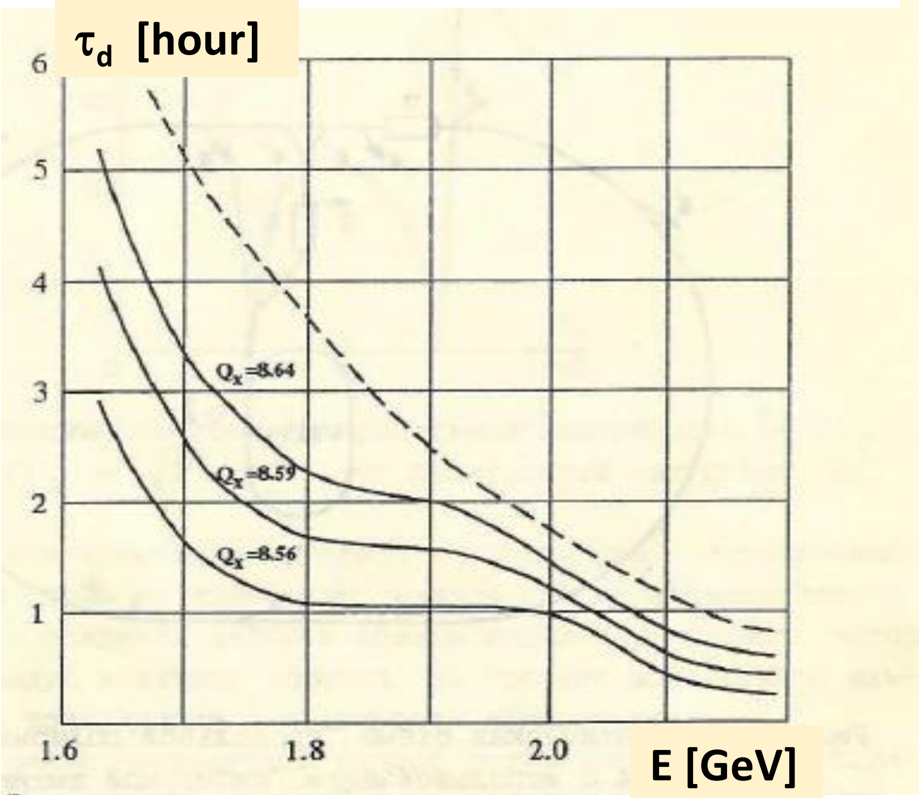
Due to the dispersion of spin rotation in the median plane around the guide field vector, quantum fluctuations lead to complete depolarization of the beam in a time that strongly depends on energy. The dependence factor is the Sokolov-Ternov radiative relaxation time. In the energy range VEPP-4 < 2 GeV it is high ~ 100 hours. Due to this, the lifetime of longitudinal polarization can reach a few hours.

What can and is important to study

- Strong dependence of the longitudinal polarization lifetime on energy ($\propto 1/E^7$)
- Depolarizing effect of betatron oscillations in comparison with calculations
- Stability of longitudinal polarization in the field of a counter beam
- The influence of transverse fields in the solenoid, arising due to orbital distortion, on polarization
- Methods for measuring longitudinal polarization

...

Example of calculated influence of betatron oscillations on radiative kinetics of polarization in one of variants of Siberian Snake scheme at VEPP-4



Depolarization time vs beam energy at different radial betatron tune. Dotted line - excluding betatron oscillations.

Two approaches to obtaining longitudinal polarization

1. **“Capital”.** Siberian Snake and injection of a polarized beam at an energy of 1.55 GeV. Expected polarization lifetime is several hours

2. **“Special”.** Obtaining longitudinal polarization with life-time of about 20 minutes without Snake and any modification of the existing complex due to the adiabatic transformation of transverse polarization into longitudinal polarization in the KEDR detector when using its field as a partial Siberian snake (to study methods for observing longitudinal polarization)

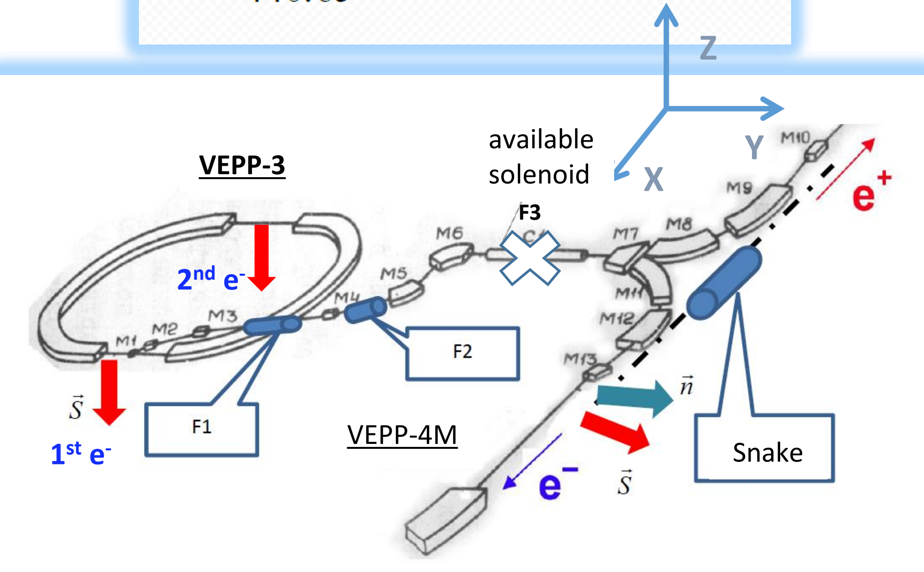
Pulse solenoids in injection beam-line at 1548 MeV

For the best matching of polarization vectors and spin-flip at the inlet, a scheme of two solenoids in the VEPP-3-VEPP-4M beam-line is proposed. You can limit yourself to one of them - **F1**. With one sign of the **F1** field, it will provide a projection ***S*$_n$=-0.97** (first bunch from VEPP-3). Otherwise ***S*$_n$ =+0.65** (second bunch)

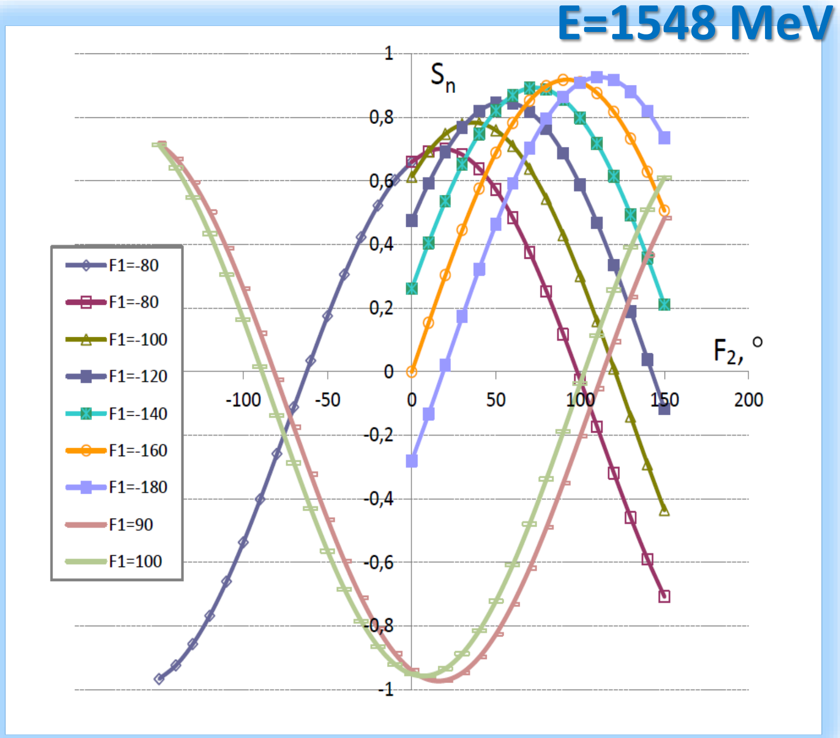
$$S_n = \vec{S} \cdot \vec{n} \quad \text{at inlet}$$

$$n_x = \sin \pi\nu, \quad n_y = \cos \pi\nu, \quad n_z = 0$$

$$\nu = \frac{E[\text{MeV}]}{440.65} = 3.513, \quad E = 1548 \text{ MeV}$$



Projection of the polarization of the injected beam onto on the equilibrium direction of polarization in VEPP-4M vs. spin rotation angles in pulse solenoids F1 and F2



F1 – angle in the solenoid between M3 and M4 (dgr)
F2 – angle in the solenoid between M4 and M5 (dgr)

Two signs of electron helicity in 3 options:

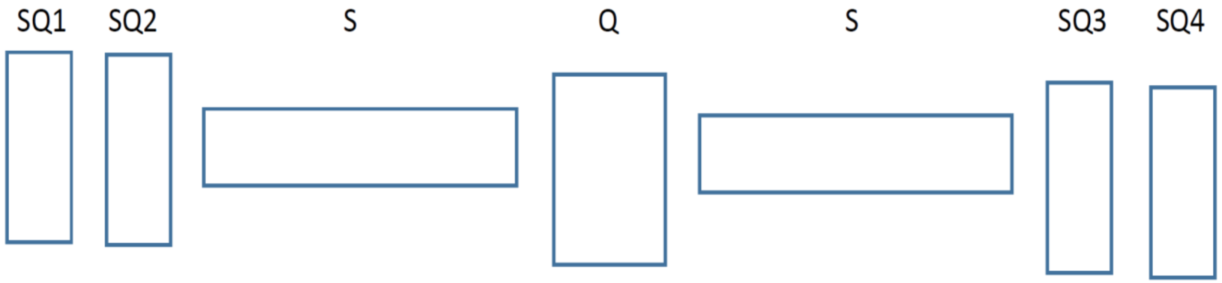
F_1=100°, F_2=0 → spin projection of 1-st bunch electrons S_n= - 0.97
F_1=80° , F_2=0 → spin projection of 2-nd bunch electrons S_n= + 0.65
F_1=120°, F_2=50° → spin projection of electrons of the second bunch S_n= + 0.85

→ no F2 needed

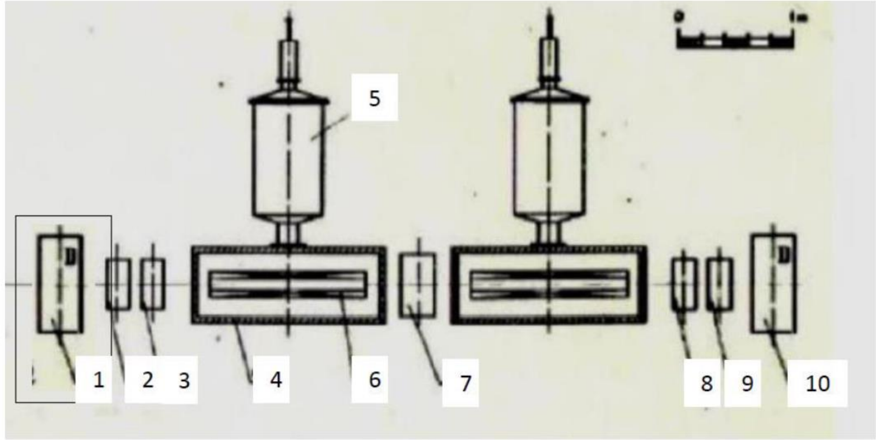
Optics of insert with Siberian Snake

Full insert length L_{total} = 532 cm, energy 1548 MэB

Solenoid length	2×1.45 m
Solenoid field	5.58 T
Gradient × length (Q)	-21.36 T/m × 0.36 m
Gradient × length (SQ1, SQ4)	-17.66 T/m × 0.24 m
Gradient × length (SQ2, SQ3)	+15.64 T/m × 0.20 m
Roll angle (SQ1, SQ4)	$+\pi/4$
Roll angle (SQ2, SQ3)	$-\pi/4$
Distance SQ1-SQ2 and SQ3-SQ4	0.07 m
Distance SQ2-Sol and Sol-SQ3	0.26 m
Distance Q-Sol and Sol-Q	0.22 m



$$M_{total} = \begin{pmatrix} L & 0 \\ 0 & -L \end{pmatrix}, \quad L = \begin{pmatrix} 1 & L_{total} \\ 0 & 1 \end{pmatrix}$$



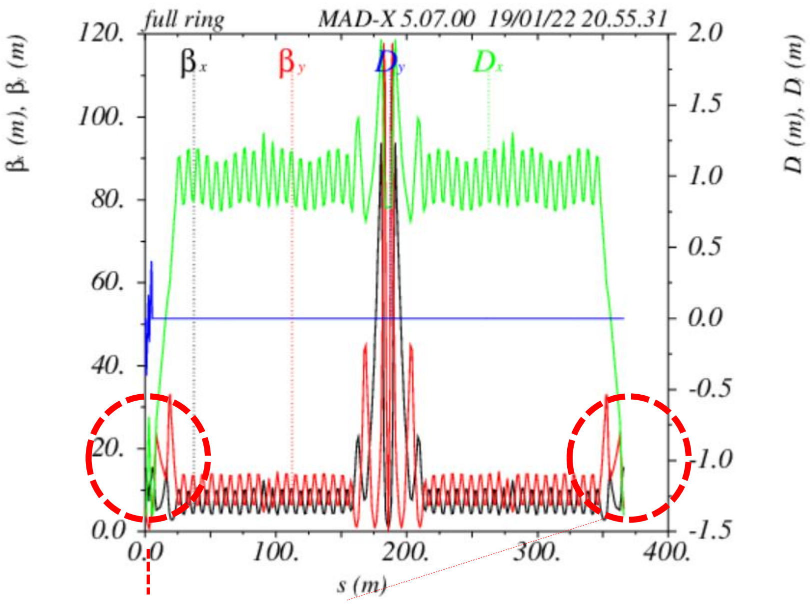
Placement of insert with solenoid on technical straight section

1, 10	basic structure elements
2, 3, 8 and 9	skew quads
4	magnetic screen
5	helium dewar
7	quadrupole lens
6	solenoid

The type of insert for localizing the betatron coupling is taken as a basis from: A.A. Zholents, V. N. Litvinenko. INP Preprint 81-80, 1981

The optics of the insert is equivalent to that of an empty section with a length equal to the length of the insert itself, but with an incursion of the betatron phase by π in one of the directions.

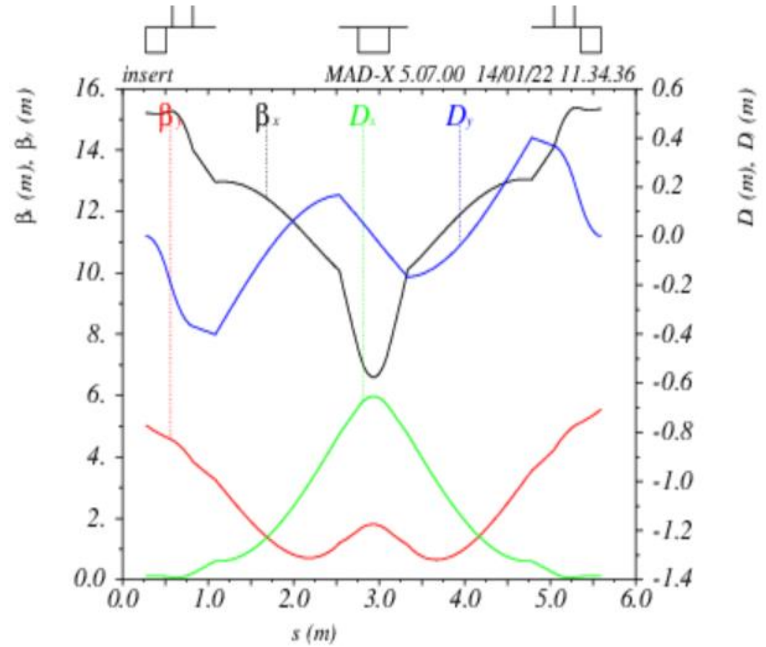
Matching VEPP-4M optics with Siberian snake



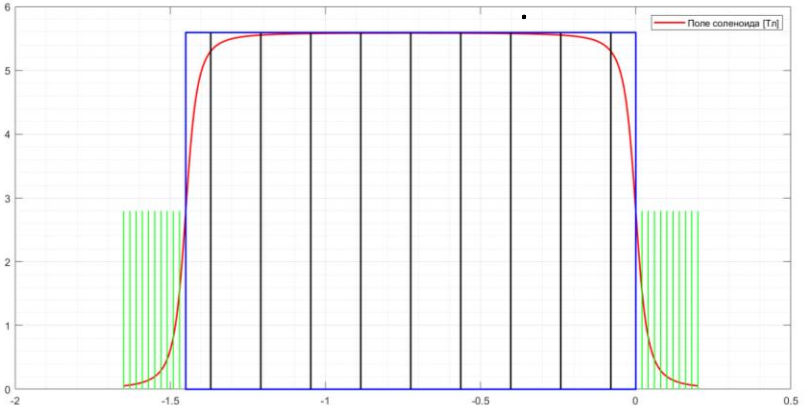
SS insertion

Tunes, chromaticity, IP
Qx = 8.539
Qy = 7.580
Cx = 1.236
Cy = -2.098
βx_IP = 0.894 [m];
βy_IP = 0.045 [m]
Emittances and energy spread @ 1548 MeV
$\varepsilon_x = 1.842 \cdot 10^{-8}$ m
$\varepsilon_y = 1.640 \cdot 10^{-14}$ m
$\sigma_E/E = 0.000252$
Damping times:
$\tau_x = 0.245$ s
$\tau_y = 0.235$ s
$\tau_t = 0.115$ s

Local perturbation of optical functions at the insertion site



Distribution of solenoid field along its axis (L_s=145 m, radius 4 cm)



Matrix of insertion with length of L_{total} :

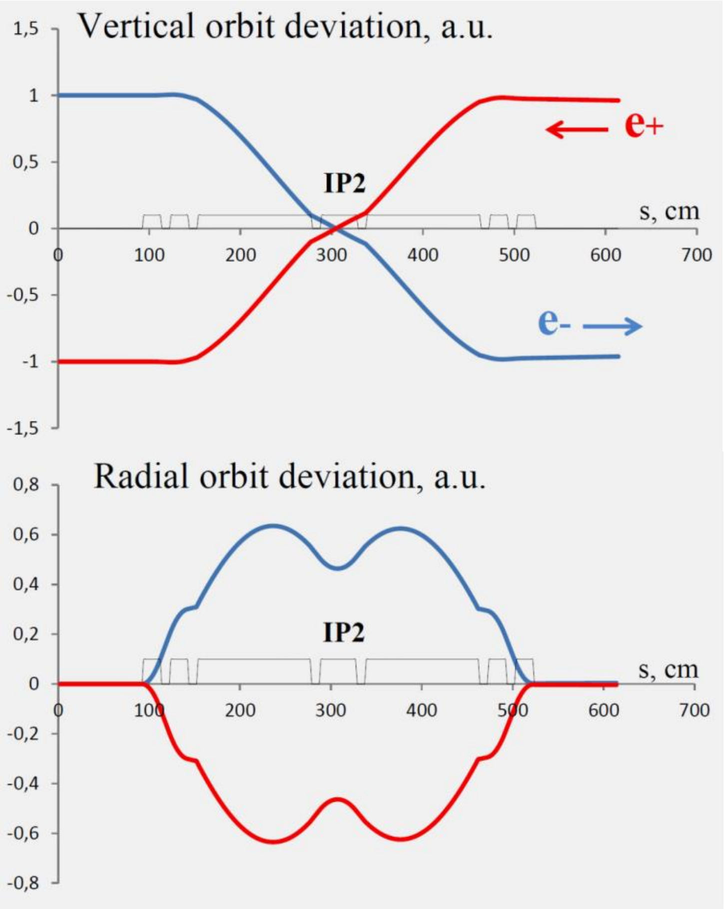
$$M_{total} = \begin{pmatrix} L & 0 \\ 0 & -L \end{pmatrix}, \qquad L = \begin{pmatrix} 1 & L_{total} \\ 0 & 1 \end{pmatrix}$$

Large phase shift and changes in chromaticity are compensated by magnetic correction in arcs

$$M_{total} = \begin{pmatrix} 1.00000 & 5.27651 & \mathbf{5.59e-15} & \mathbf{-4.54e-15} \\ -1.25e-15 & 1.00000 & \mathbf{1.70e-15} & \mathbf{3.43e-15} \\ \mathbf{-5.16e-15} & \mathbf{5.77e-15} & -1.00000 & -5.28651 \\ \mathbf{-2.11e-15} & \mathbf{-3.55e-15} & 2.81e-15 & -1.00000 \end{pmatrix}$$

Taking into account separation of orbits at insert site and IBS

Orbit separation along insertion (at input ± 4 cm)

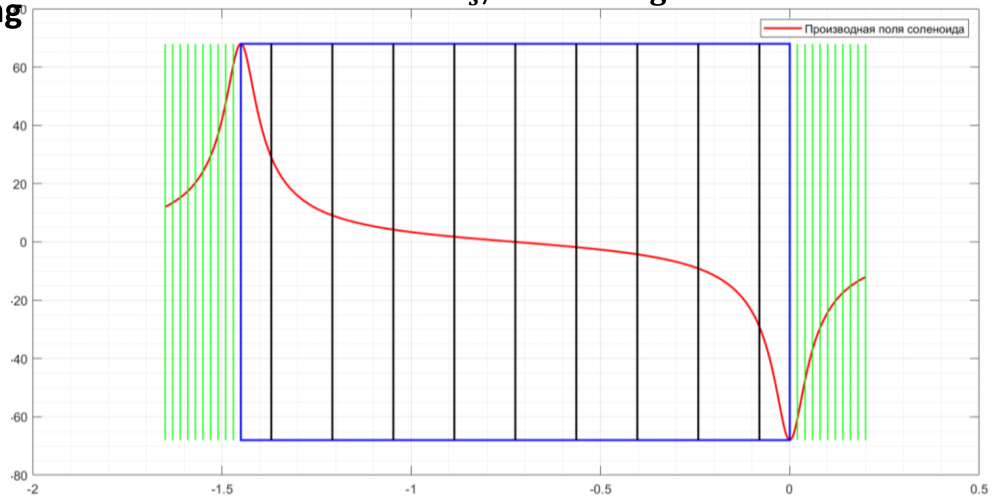


Transverse solenoid fields taking into account orbital deviation from solenoid axis:

$$B_y \approx -y \frac{d}{ds}\frac{B_s}{2} + B_s \frac{dx}{ds}$$

$$B_x \approx -x \frac{d}{ds}\frac{B_s}{2} + B_s \frac{dy}{ds}$$

Field derivative dB_s/ds along solenoid axis



w/o IBS

Emittances and energy spread

$\varepsilon_x = 1.455 \cdot 10^{-8}$ m

$\varepsilon_y = 8.797 \cdot 10^{-12}$ m

$\sigma_E / E = 0.000269$

Damping times

$\tau_x = 0.194$ s

$\tau_y = 0.236$ s

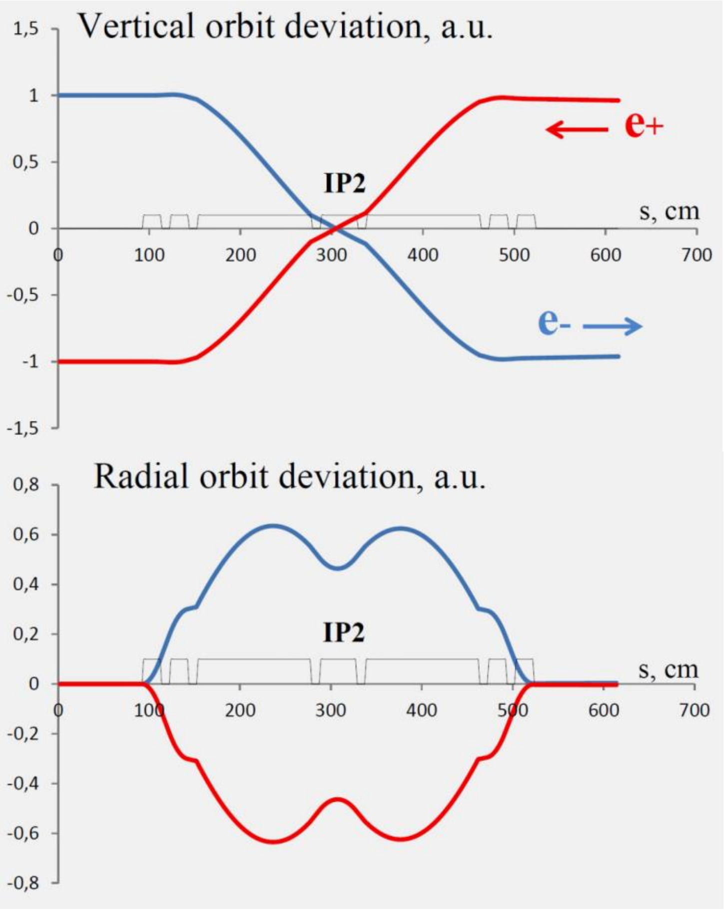
$\tau_t = 0.131$ s

Emittances and energy spread with IBS
I=10 mA, E=1548 MeV

	w/o separation	with separation
ε_x[m]	$3.302 \cdot 10^{-8}$	$2.634 \cdot 10^{-8}$
ε_y[m]	$2.712 \cdot 10^{-10}$	2.898^{-10}
σ_E / E	0.000336	0.000359

Taking into account separation of orbits at insertion site and IBS

Orbit separation along insertion (at input ± 4 cm)



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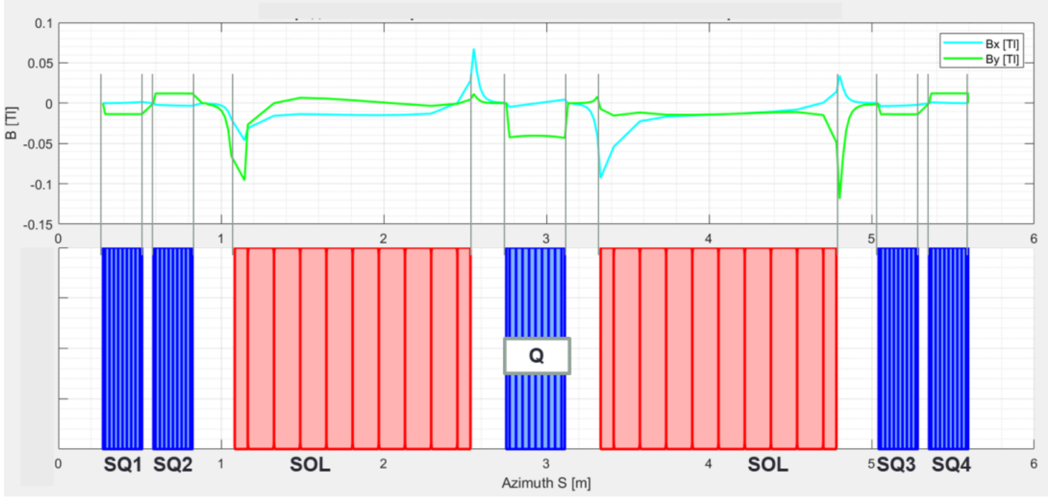
Transverse fields along the solenoid insertion [T]



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ε_x[m]	$3.302 \cdot 10^{-8}$	$2.634 \cdot 10^{-8}$
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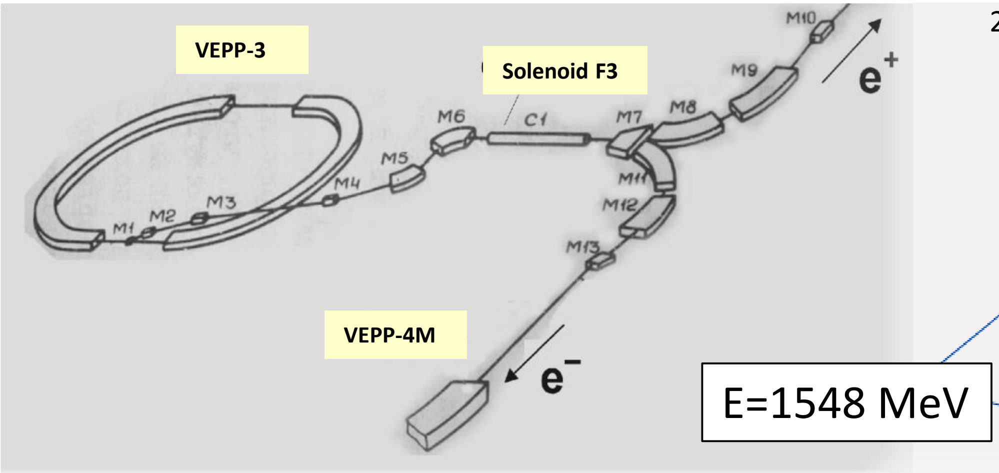
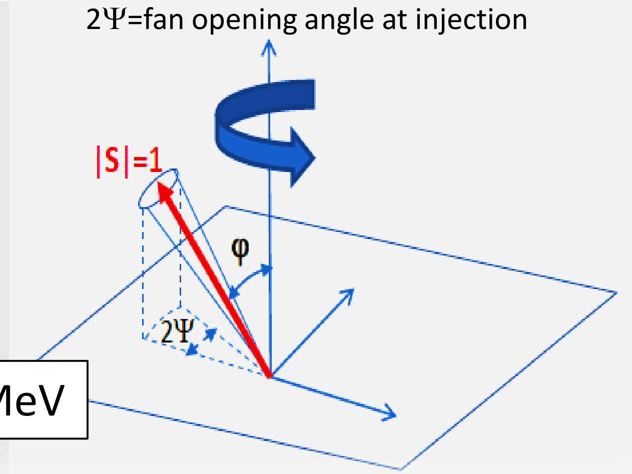
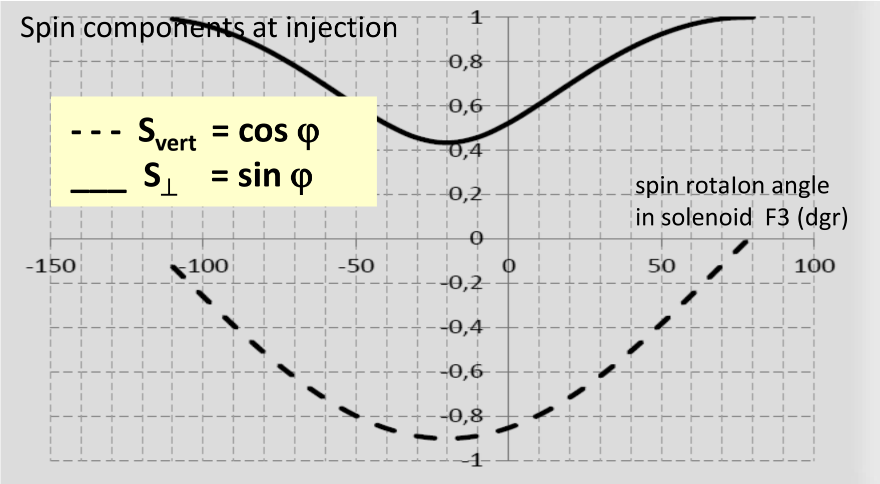
$\boldsymbol{\sigma_E / E}$	0.000336	0.000359

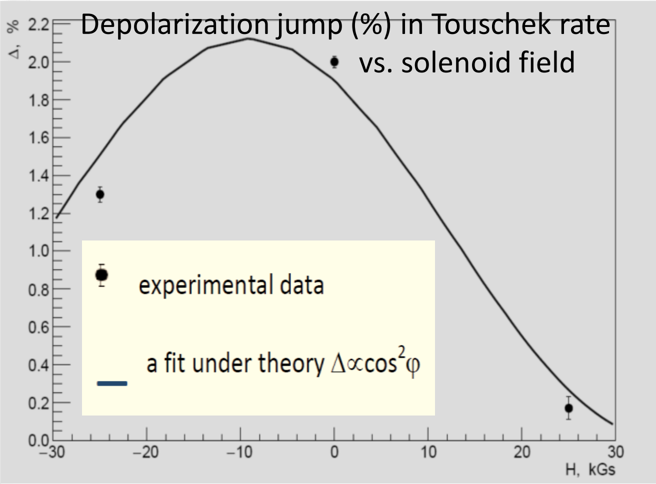
Injection experiment with different polarization inclination to guiding field

V.V. Kaminsky, V.A. Kiselev, E.B. Levichev, S.A. Nikitin, I.B. Nikolaev, P.A. Piminov, A.N. Zhuravlev









Depolarization jump in Touschek scattering rate

$\Delta \propto \exp(-\Psi^2)\cdot\sin^2\varphi + \cos^2\varphi$

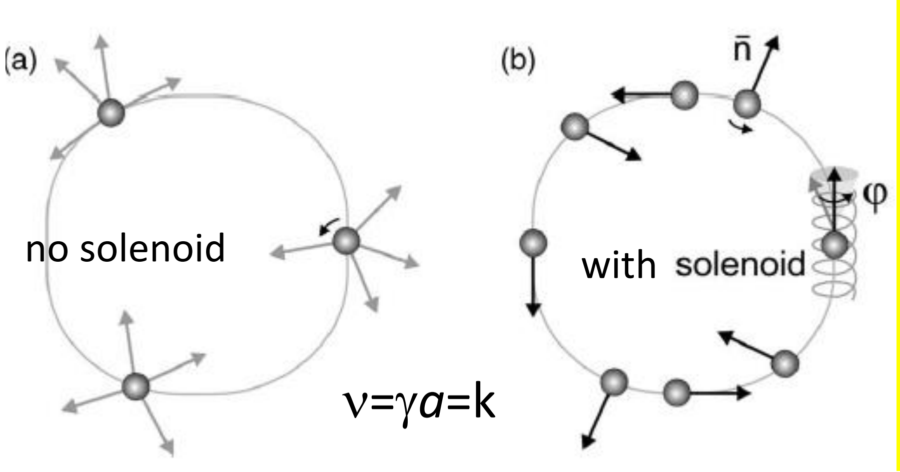
If $\Psi \ll 1$ (Fan polarization) then jump Δ does not depend on φ (solenoid field)!

If $\Psi \geq 1$ (no Fan polarization) then $\Delta \propto \cos^2\varphi$

Based on dependence of jump on solenoid field, one can determine the preservation of Fan polarization after injection after time required to use Touschek polarimeter (~ 10 min).

Although there are few measured points, their location suggests that $\Delta \propto \cos^2\varphi$. This is compatible with the conclusion that the experiment corresponds to the calculation of spin kinematics in the injection beam-line of complex 3D geometry. It is estimated that the initially narrow polarization fan spreads out over a time on the order of the radiative damping time due to the quadratic nonlinearity of the field (chromaticity correction system)

Adiabatic transformation of transverse polarization into longitudinal



=any value
not too small

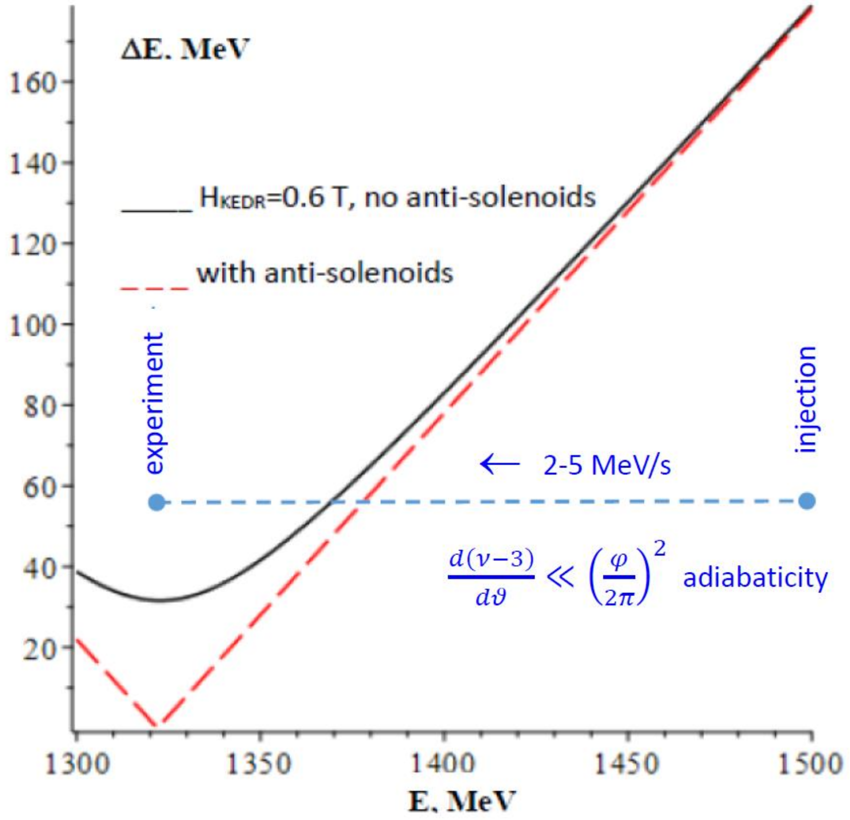
$$\varphi \approx \frac{\pi}{4.6\nu} \cdot \int H_{||} ds \approx 0.45 \text{ rad}$$

$$\tau_d \sim \frac{54}{132} \frac{\tau_{ST}}{\pi^2 \nu^2} \varphi^2 \approx 20 \text{ min}$$

$H_{||} = H_{KEDR}$ =0.6 T

E=1320 MeV

Detuning from resonance **ν=γa=3** vs energy

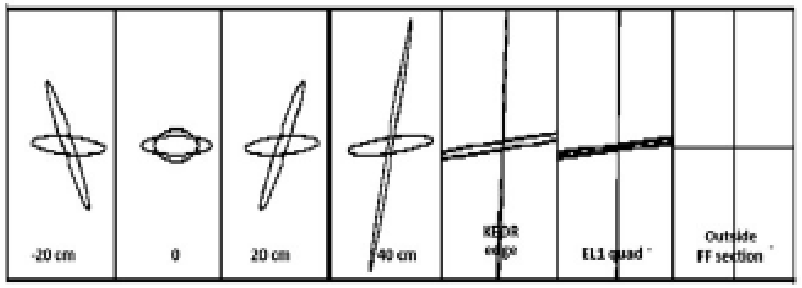


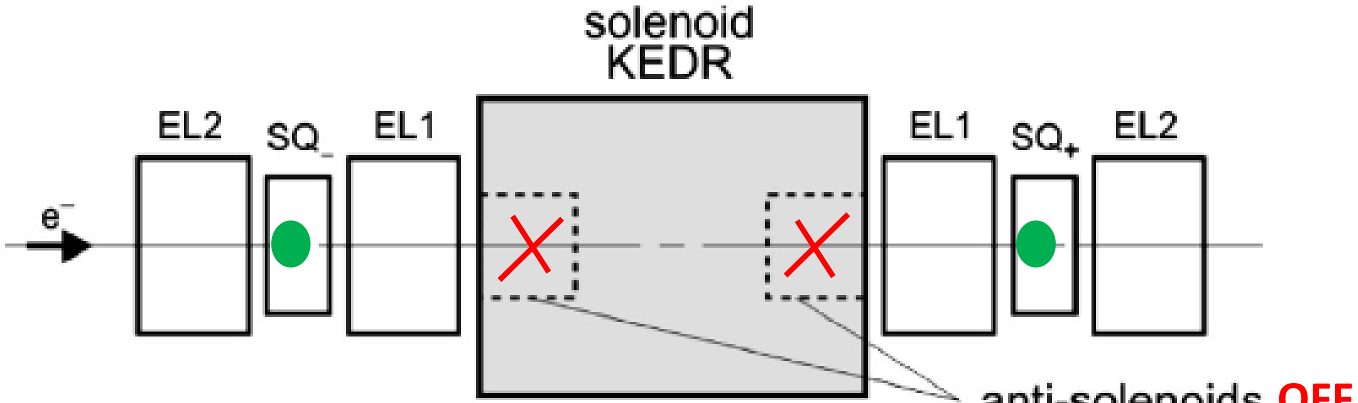
- Inject a transversely polarized beam from VEPP-3 at E=1500 MeV
- Turn off anti-solenoids, turn on special skew-quad correction instead
- Reduce energy to 1320 MeV (ν =3) at rate of ~ several MeV/s
- Longitudinal polarization lifetime at 1320 MeV is about 20 minutes (Sokolov-Ternov polarization time is about 400 hours)
- Measure longitudinal polarization by changing the intensity of Compton scattering when switching the sign of circular polarization polarization of laser photons and using a scattered electron detection system (both systems are active at VEPP-4M)
- In addition, the fact of the presence of polarization can be checked with a Touschek polarimeter together with resonant depolarization (by change in the ratio of the counting rates of Touschek electrons from polarized and unpolarized bunches)

Coupling compensation for KEDR field with two skew quadrupoles

when transforming transverse polarization into longitudinal

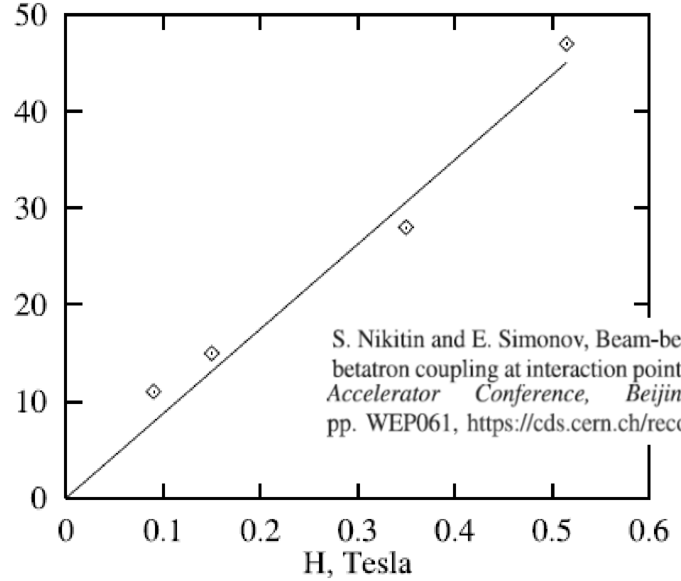
View of normal modes of transverse oscillations at different distances from center of KEDR





S. Nikitin and I. Protopopov, Report No. BINP SB RAS 1999-44, 1999.

Vertical size [μm] in IP calculated and measured by specific luminosity vs. KEDR field at 1.5 GeV in “two skew quads” compensation scheme



S. Nikitin and E. Simonov, Beam-beam effects with strong betatron coupling at interaction point, in *2nd Asian Particle Accelerator Conference, Beijing, China, 2001*, pp. WEP061, https://cds.cern.ch/record/914729?ln=ru.

KEDR field H_K= 0.6 Tesla.
Gradient/current in windings $SQ_{\pm}$=±120 G/cm/14 A
is proportional to the field H_K and does not depend on energy

Excluding IBS (E=1.32 GeV, H_K=6 kG) :

$$\sigma_y^* = 7\left[\frac{\text{cm}}{\text{kG}}\right] \times H_K\ [\text{kG}] \times \frac{\sigma_x^*(E)}{\beta_x^*} = 56\ \mu\text{m}$$

Compensation for coupling introduced by the detector field provides better beam control during acceleration/deceleration with anti-solenoids turned off. The scheme has been successfully used to cross an integer spin resonance at 1763 MeV

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

Minimum program

1. **Experiment on transforming transverse polarization into longitudinal. Test observation of longitudinal polarization**
2. **“Siberian snake” experiment:**

- design and manufacture of two SC solenoids with an integral of at least 145 cm × 5.6 T; 5 “warm” quadrupoles (4 skew and one normal of approximately 3 kG/cm) and a vacuum chamber;
- development or selection of power sources for insert magnets;
- installation of the insert in the center of the technical straight section;
- manufacturing a pulse solenoid with a field integral of up to 5 T·m and its placement in the injection beam-line between the bending magnets M3 and M4;
- in addition to it, transfer existing solenoid F3 (of 5 T·m) to the place mentioned above to obtain a total integral of 9.1 T m;
- conducting an experiment to obtain longitudinal polarization of electrons with helicity of two signs (S_n=-0.97 and S_n=+0.65) at 1548 MeV;
- study of factors influencing the lifetime of longitudinal polarization (energy, betatron oscillations, orbital distortions, colliding beam, IBS …);
- debugging methods for measuring the degree of longitudinal polarization

Thanks for attention!

Acknowledgement

Authors thank:
A. Blinov and A. Milshtein; V. Kiselev and O. Gordeev; A. Bomyagkov and S. Sinyatkin;
N. Mezentsev; I. Nikolaev and V. Kaminsky for discussions

Thanks for attention!