OBSERVATION OF SAW-TOOTH EFFECT ORBIT AT VEPP-4M COLLIDER

E. Bekhtenev, G. Karpov, D. Leshenok[1], S. Nikitin, O. Plotnikova,

Budker Institute of Nuclear Physics, Novosibirsk, Russia
[1] also at Novosibirsk State University

Motivation

There is specific distortion of the e^- and e^+ closed orbits due to the radiation losses. This distortion is called the Saw-Tooth effect orbit.

In precision experiments related to energy calibration with respect to the spin precession frequency, the Saw-Tooth effect can play a significant role, e.g. in the projected FCC-ee (CERN) and CEPC (China) super colliders.

Also this effect can be important when precision comparing the spin precession frequencies of electrons and positrons (CPT invariance test in the storage mono-ring).

Contents

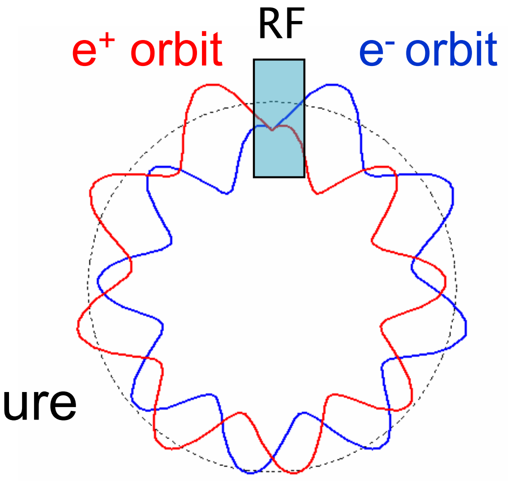
Objectives:

Our experiment was carried out at a high energy of the VEPP-4M (4.1 GeV). And this experiment was not directly related to the CPT invariance test.

Our goals:

- The study of the degree of agreement between the theoretical model and the real conditions of the VEPP-4M
- The revealing of the magnitude of the time dependent fluctuations of the difference between the electron and positron orbits

CPT Symmetry Test at the Storage Ring



- Spin precession frequency $\Omega = \nu\Omega_0 = q'\langle H\rangle$,

  $q' = \left[\frac{g-2}{2}\right]\cdot\left(\frac{e}{mc}\right), \nu = \gamma\left[\frac{g-2}{2}\right]$

- Revolution frequency $\Omega_0 = ec\left\langle\frac{H}{E}\right\rangle$ is the same for e^+ and e^-, but the orbits aren't coincident like in Figure

- If CPT is true then $\langle H\rangle_+ = \langle H\rangle_-$ in machine with the mirror symmetry, so $\Omega_+ = \Omega_-$

- If, $e^+ \neq e^-, m_+ \neq m_-$ then $\Omega_0^+ = \Omega_0^- \rightarrow$ e+ and e- orbits differ from those of the mirror symmetry type and thus $\langle H\rangle_+ \neq \langle H\rangle_-$

- Beside, generally $q'_+ \neq q'_-$ (anomalous parts of gyromagnetic ratio)

- Ideal storage ring with the mirror symmetry but without electrical fields:

$\Delta\Omega = \Omega_+ - \Omega_- = q'_+\langle H\rangle_+ - q'_-\langle H\rangle_- \neq 0$ due to CPT symmetry violation

Scheme of VEPP-4M

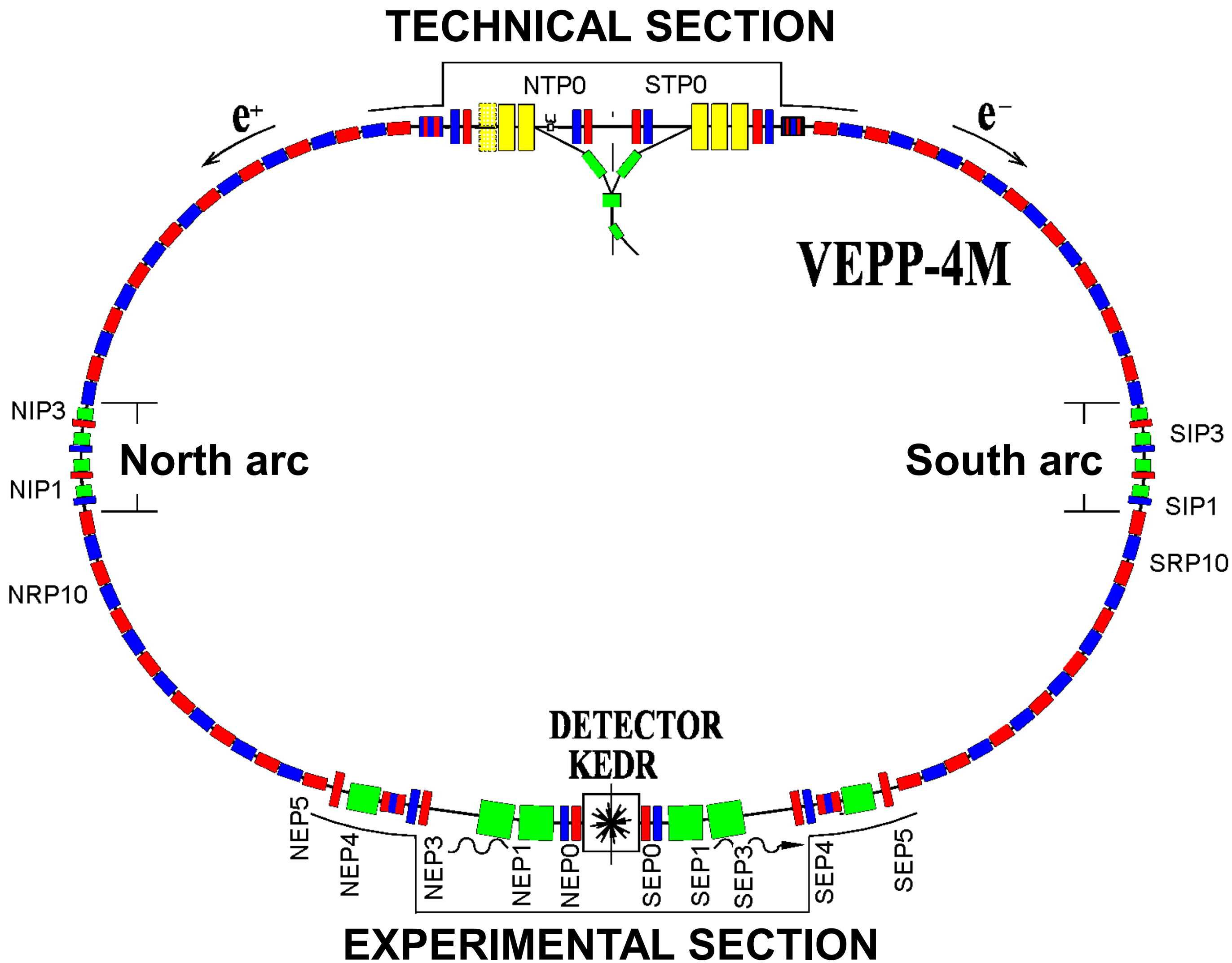


Figure shows positions of BPMs near four interaction points (IPs).

BPM System

- There are 54 BPMs at VEPP-4M collider
- The BPMs make turn-by-turn measurements with a frequency of 0.8 MHz
- The equilibrium orbit is calculated by averaging the turn-by-turn data in a period of 20 ms
- The wide bandwidth (200 MHz) enables separation of measurements of electron and positron bunches with a time interval between bunches of up to 18 ns and a beam length of about 1.5 ns.
- For reducing the measurement error caused by overlapping of the electron and positron signals, the program compensation for the signal “tail” is implemented in the system. The digital compensation decreases the position measurement error for the second bunch 3 to 5-fold.

Energy losses effect on the orbit

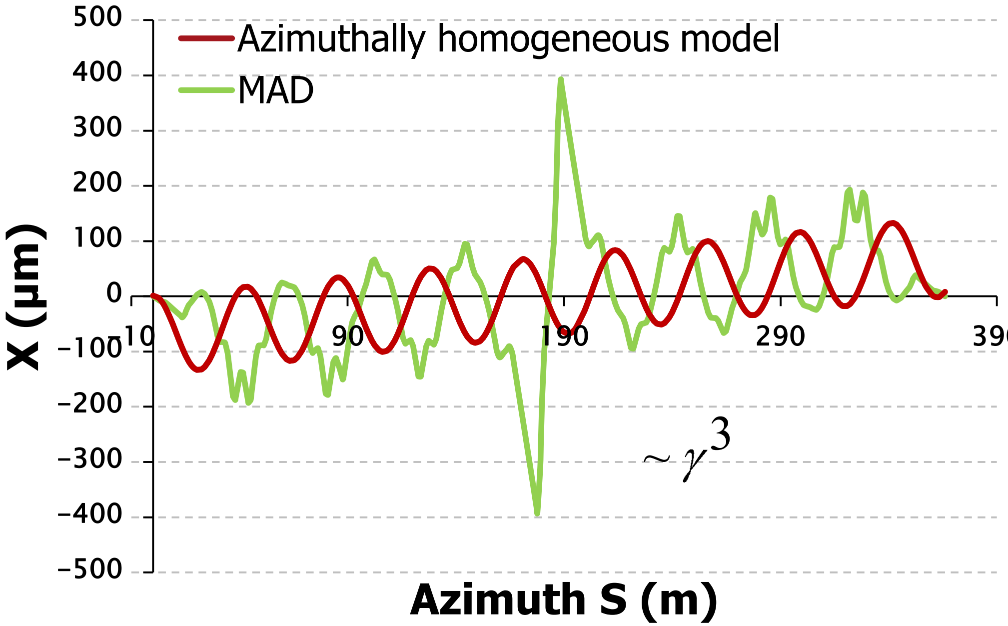
$$U_0 = C_\gamma E_0^4 R\langle K^2 \rangle$$ Total energy losses per revolution in the ring

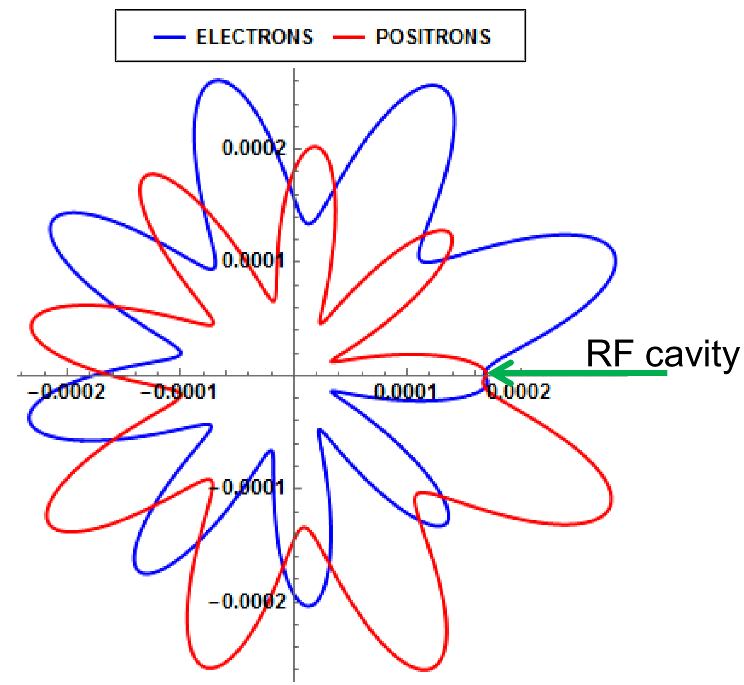
U_0 = 30 keV, E_0 = 1.85 GeV
U_0 = 726 keV, E_0 = 4.1 GeV

$$x''(s) + \frac{\nu^2}{R^2} x(s) = \frac{U_0 K}{E_0}\left(\frac{1}{2} \mp \frac{s}{2\pi R} \pm \Theta(s - 2\pi R)\right)$$

The equation of motion for e^- and e^+ in the median plane in the azimuthally homogeneous model (Θ is the Heaviside function)

Positron orbits for E = 4.1 GeV





The maximum value of the difference between the electron and positron orbits is ~1 mm.

The e^- and e^+ orbits in the azimuthally homogeneous model

Influence of mirror symmetry breaking on electron and positron energy difference

$$E^{(1)}(\theta) = E_0 \cdot [1 + f^{(0)}(\theta)]$$

E_0 is equilibrium energy in the absence of loss

$$f^{(0)}(\theta) = \frac{\overline{U}^{(0)}}{2} - \frac{P_\gamma R}{E_0 c} \int_0^\theta \left[1 + \frac{\Delta H(\theta)}{H_0}\right]^2 d\theta$$

function describing the azimuthal distribution of losses in the zeroth approximation

$$f^{(1)}(\theta) = \frac{\overline{U}^{(1)}}{2} - \frac{P_\gamma R}{E_0 c} \int_0^\theta \left[1 + 2 \cdot \left(f^{(0)}(\theta) + \frac{\Delta H(\theta)}{H_0} \right)\right] d\theta$$

function of azimuthal distribution of losses in the first-order approximation

$$\frac{\langle E_- \rangle - \langle E_+ \rangle}{E_0} = \langle f_- \rangle - \langle f_+ \rangle - \frac{\langle K \eta_X f_- \rangle - \langle K \eta_X f_+ \rangle}{\langle K \eta_X \rangle}$$

$K(\theta)$ is the curvature function

η_X is the dispersion function

For initially azimuthally homogeneous model at E = 1.85 GeV

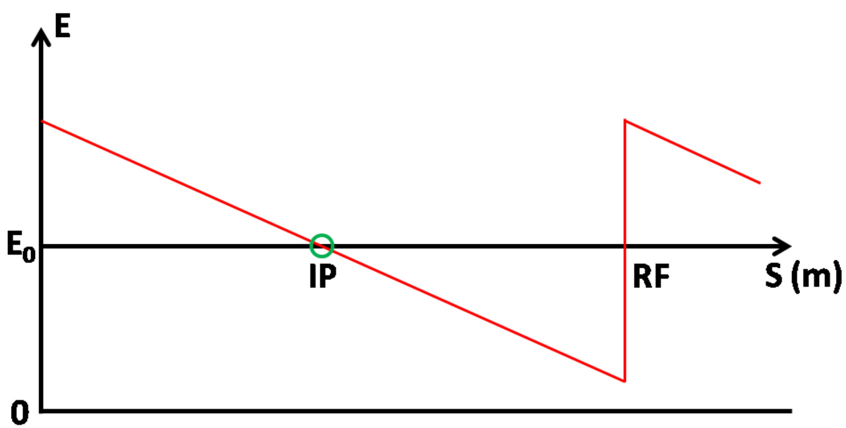
- Radius is 38 m (average radius of the bending magnets)
- Storage ring was divided into 500 elements.
- Spread of random perturbation of the magnetic field $\frac{\Delta H}{H_0} = 10^{-3}$

$$\frac{\langle E_- \rangle - \langle E_+ \rangle}{E_0} = 2 \times 10^{-12}$$

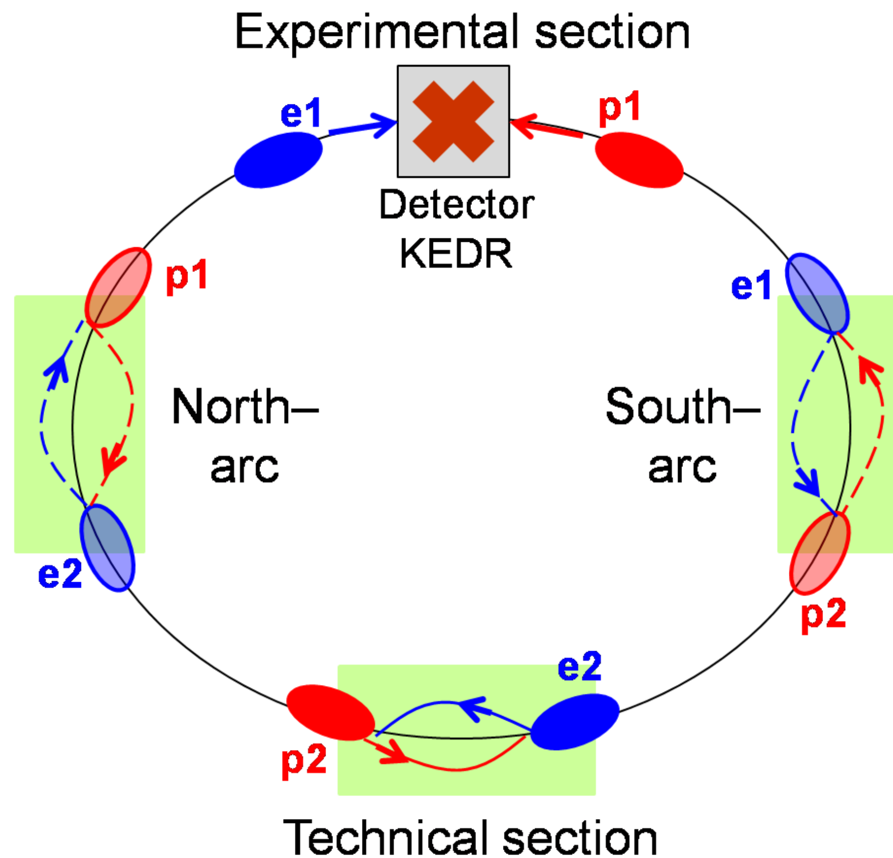
Experiment to observe the Saw-Tooth orbit

Experimental conditions

- E = 4.1 GeV
- T_{observ} = 5.5 hours
- 2 2 bunch mode, the beams interact in IP0 (detector KEDR)
- The KEDR field is turn off



Saw-Tooth effect in particle energy distribution along the storage ring



Configurations of electron and positron bunches collision with a spatial quarter-revolution interval.

The horizontal coordinate of the e^- ("–") and e^+ ("+") bunches on the BPMs

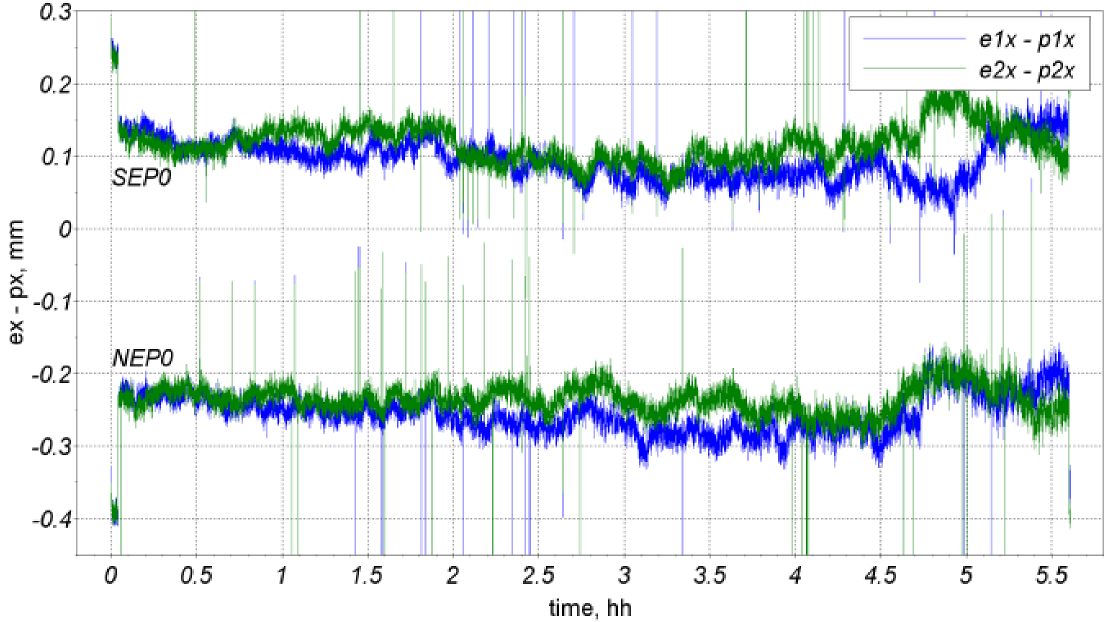
$$X^{\mp} = X_R^{\mp} + X_M^{\mp} + X_Z^{\mp} + X_E^{\mp} + \ldots$$

X_R – the deviation caused by the radiation loss,
X_M – the contribution due to perturbations of the magnetic structure,
X_Z – the change associated with local coherent energy loss to chamber impedance,
X_E – the contribution of electrostatic fields.

The difference in the orbits does not depend on the contribution of time-unstable magnetic disturbances

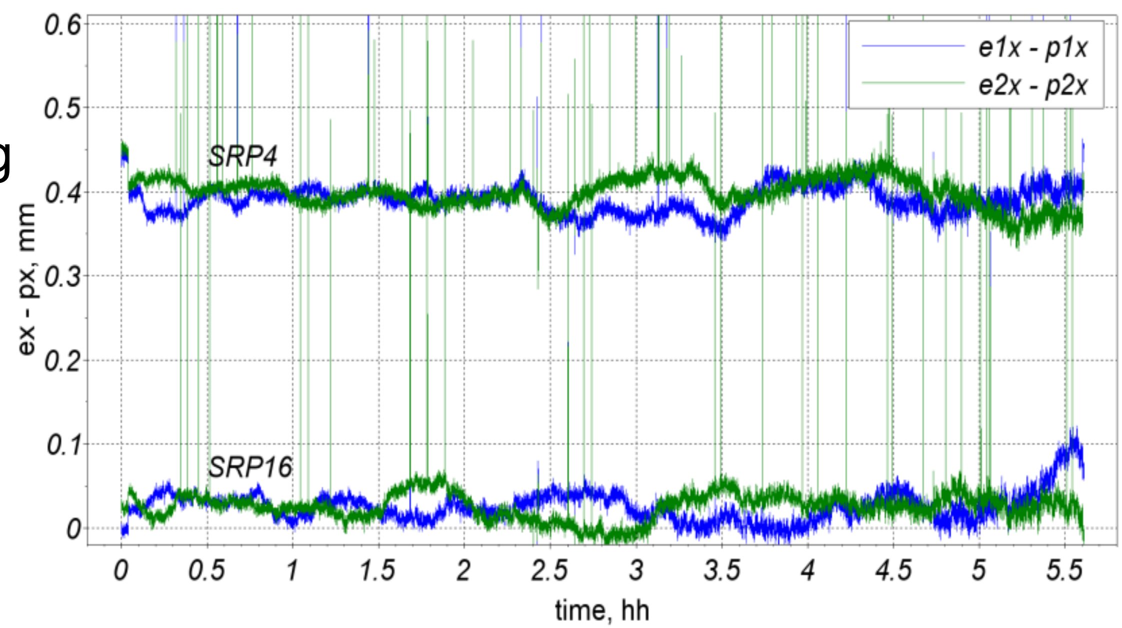
$$\Delta X = \Delta X_R + \Delta X_Z + \Delta X_E + \ldots$$

Example of the e$^-$ and e$^+$ orbits comparison on BPMs

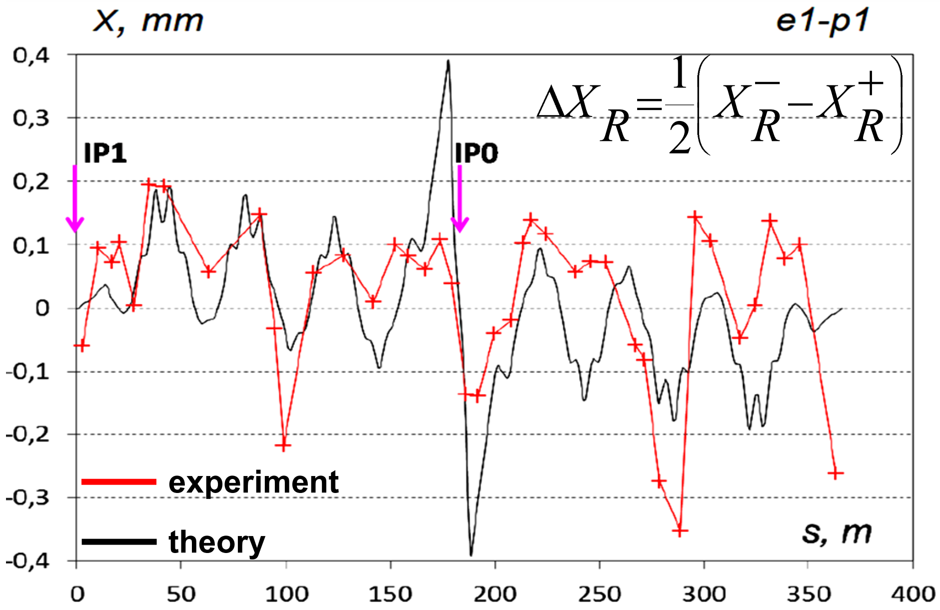


Two BPMs near the IP0 (detector KEDR). Difference in e$^+$e$^-$ radial orbits in pairs of counter bunches.

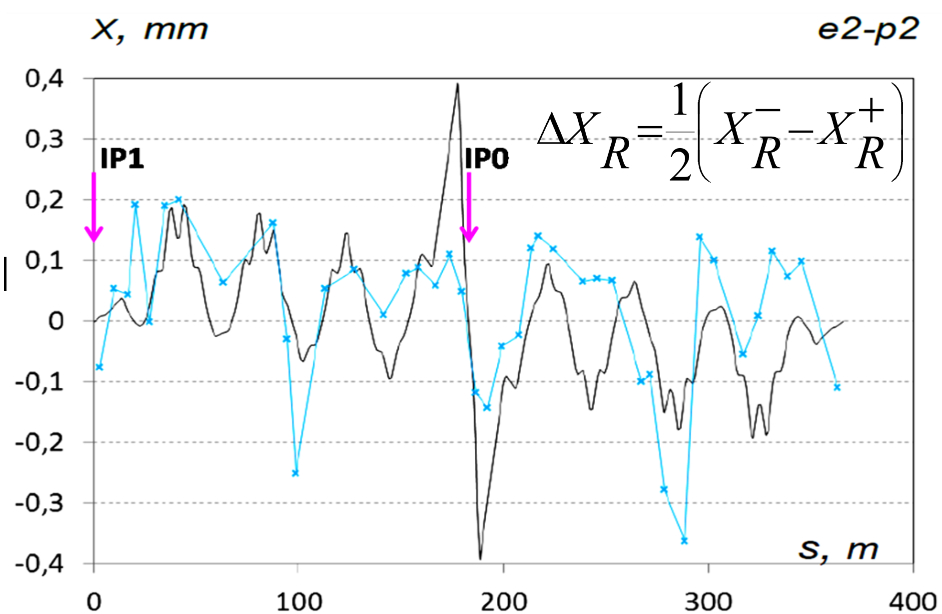
Two BPMs at the beginning and end of the South-arc. Difference in e$^+$e$^-$ radial orbits in pairs of counter-bunches.



Comparison with theory

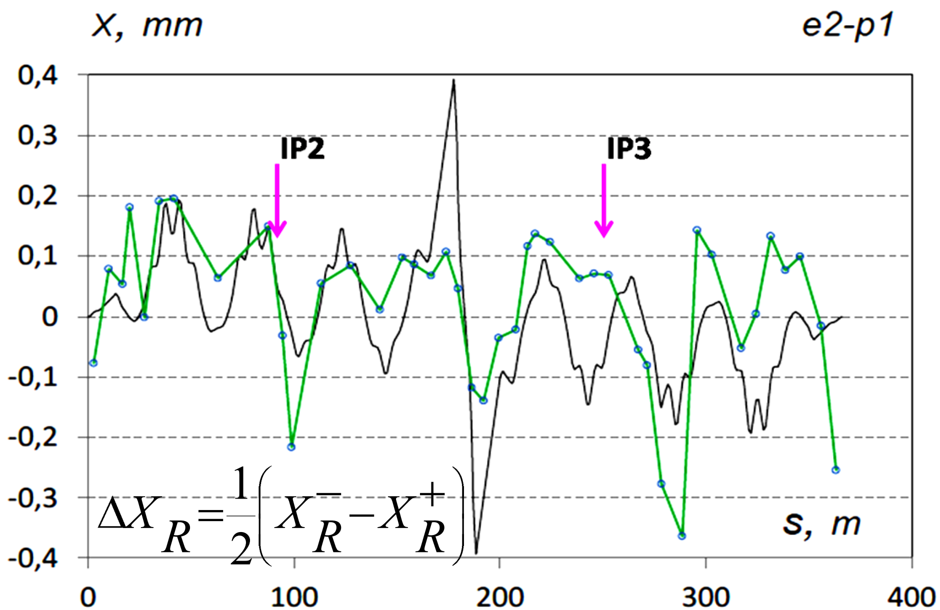


Normalized radial orbit of e$^-$.
Interaction points: KEDR detector and center of technical section (marked by arrows).

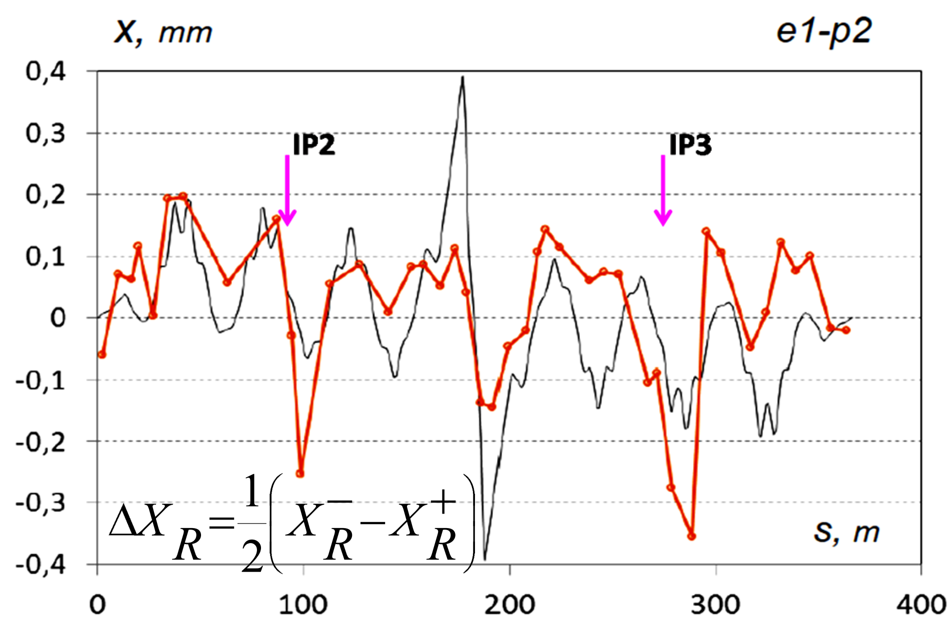


Normalized radial orbit of e$^-$.
Interaction points: center of technical section and KEDR detector.

Comparison with theory

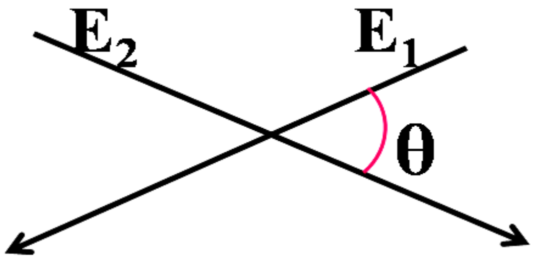


Normalized radial orbit of e⁻.
Interaction points: centers of North-arc and South-arc.



Normalized radial orbit of e⁻.
Interaction points: centers of South-arc and North-arc.

Crossing angle due to the Saw-Tooth effect



Intersection of beams in KEDR detector

Crossing angle on ϒ-peak energy is
$\theta = 2.23\ \ 10^{-4}$ rad due to Saw-Tooth effect

$$M^2 = 2E_1E_2\left(+\cos\theta\right)$$ Invariant mass

$$\frac{\Delta M}{M} = -\frac{\theta^2}{8} \approx 10^{-8}$$

Center-of-mass energy shift
(for ϒ-peak energy 2 4.73 GeV)

Errors sources and their magnitude

"Tails" of signals on BPMs located close to IPs

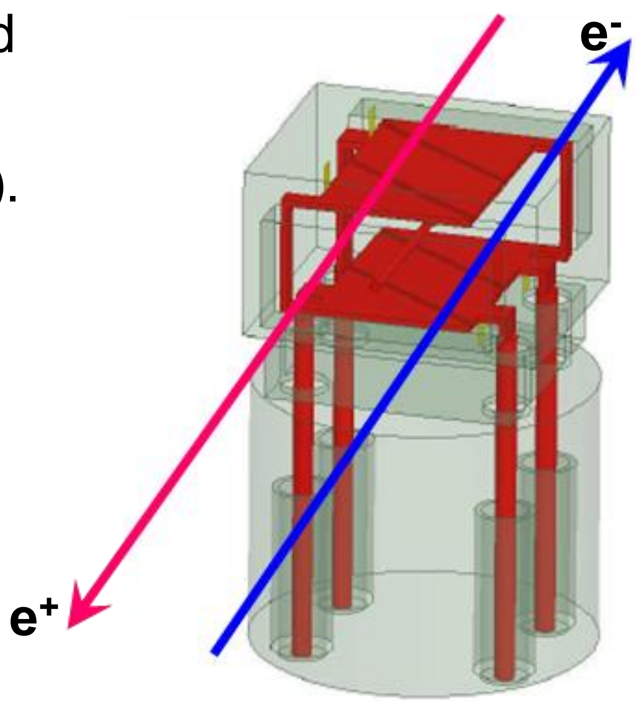
The measurement error increases for the chronologically second bunch in a colliding pair.

Echo signals

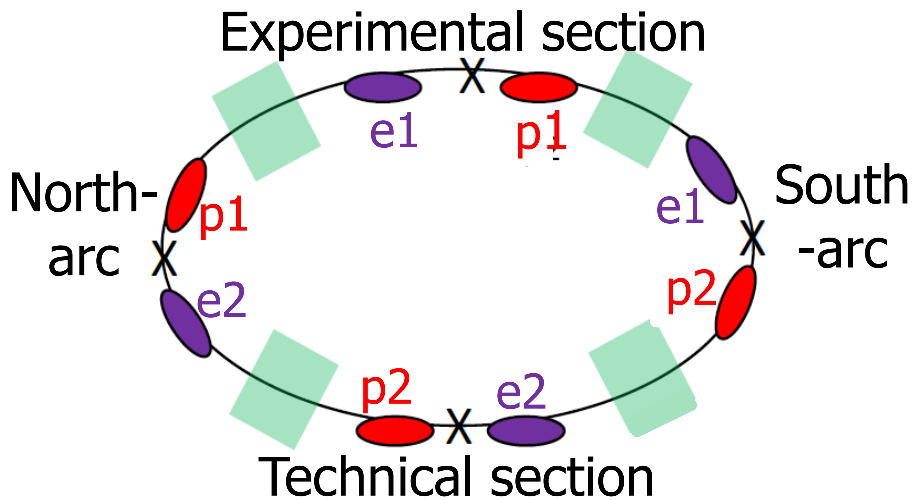
Generated by bunch on sharp transitions in the size of the vacuum chamber. They are reflected at the ends of the section with transitions and "live" many turns (trapped waveguide).

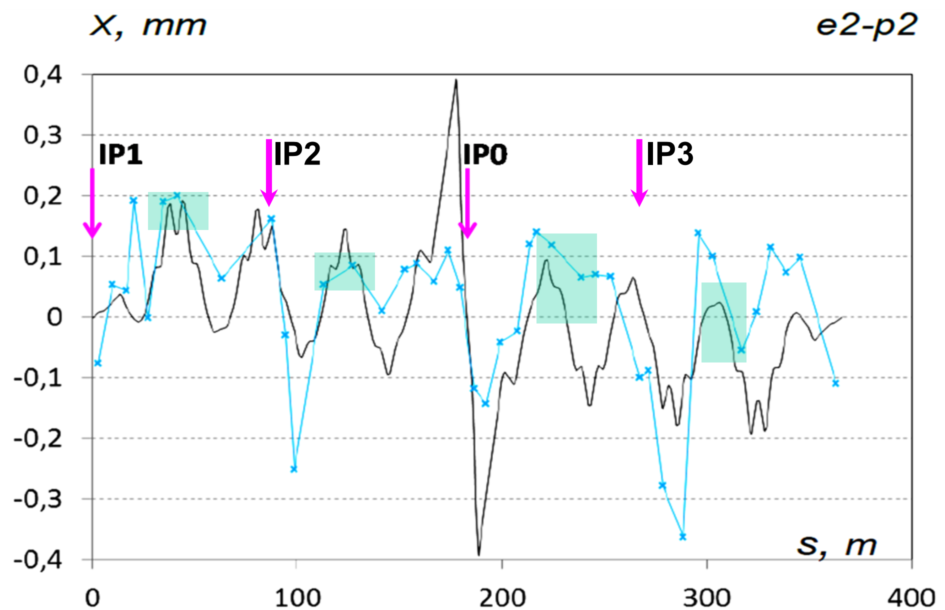
The asymmetry of some BPMs design

Which is due to the sensitivity of the sign of the direction of the particle velocity.



Areas with minimum influence of signals "tails" in 2 2 mode





Green marked areas with a minimum effect of “tails”

IP0 – KEDR detector
IP1 – center of technical section
IP2 – center of S-arc
IP3 – center of N-arc

Conclusion

- An experiment to observe the Saw-Tooth effect orbit based on measuring the difference of the e^- and e^+ closed orbits was carried out at the first time

- A comparison of the calculated model of the Saw-Tooth effect orbit with the measured data has been made. There is a qualitative agreement between the theoretical and the experimental data. And the observed deviations can be explained by the features of measurements that exist under the experimental conditions

- Quantitative estimates of the influence of errors related to the Saw-Tooth effect orbit on the accuracy of the precision experiments (CPT invariance test and measurement of the Υ-meson mass) have been obtained

Thank you for attention.