V. Kiselev, for the VEPP-4 team

PARTICLE AND ACCELERATOR PHYSICS AT THE VEPP-4M COLLIDER

7 October 2014
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VEPP-4 accelerator facilities

**Mono-ring collider** with $2e^+ \times 2e^-$ bunches and electrostatic orbit separation in 3 parasitic IPs

$2E = 2.11 \text{ GeV}$

$L = 2 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$

$L = 8 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$

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**Parameters at 1.8 GeV**

- Circumference, $P$ (m): 366.075
- Revolution frequency, $f_0$ (kHz): 818.924
- Revolution period, $T_0$ (ns): 1221
- Maximum energy, $E$ (GeV): 5.3
- Momentum compaction factor, $\alpha$: 0.017
- Betatron tunes, $Q_1/Q_2$: 8.54/7.58
- Synchrotron tune, $Q_3$: 0.012
- Natural chromaticity, $\xi/\xi_0$: $-14.5/-20.3$
- Damping times, $\tau/\tau_1/\tau_2$ (ms): 70/35/70
- Horizontal emittance, $\varepsilon_x$ (nm-rad): 17
- Energy spread, $\sigma_E/E$: $4 \times 10^{-4}$
- Bunch length, $\sigma_\tau$ (cm): 6
- Energy loss/turn, $\Delta U$ (keV): 16
- IP optical functions, $\beta_1 / \beta_2 / \eta_2$ (m): 0.05/0.7/0.78
VEPP-4 complex pictures

New experimental station for fast processes study at VEPP-4M

7-pole electromagnet wiggler Installed recently at VEPP-4M

RF separation system

VEPP-4M arc

Internal gas target for nuclear physics at VEPP-3 (Deuteron)

VEPP-4M arc

Electron tagging system for two-photon experiments
Compton backscattering system

Detector KEDR

SR experiments at VEPP-3
High-energy physics: some advantages of VEPP-4 - KEDR

• Unique beam energy range from 0.9 up to 5.5 GeV;

• Measurement of the beam energy using resonant depolarization method with the record accuracy $10^{-6}$, not reached at any other laboratory of the world;

• Routine monitoring of the beam energy using the Compton backscattering method with the accuracy of $5 \cdot 10^{-5}$;

• Universal detector KEDR comparable with modern detectors used for high-energy physics experiments at the electron-positron colliders:
  - system of registration of scattered electrons and positrons with the record resolution $10^{-3}$,
  - the fine energy and spatial resolution in a LKr calorimeter (3.5% and 1 mm, $E = 1.8$ GeV),
  - system of aerogel Cerenkov counters.
### Mass measurements at VEPP-4: history

<table>
<thead>
<tr>
<th>Particle</th>
<th>$E$, MeV</th>
<th>Accuracy, $\Delta E/E$</th>
<th>Detector</th>
<th>Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi$</td>
<td>$3096.93\pm 0.10$</td>
<td>$3.2\cdot 10^{-5}$</td>
<td>OLYA</td>
<td>1979-1980</td>
</tr>
<tr>
<td>$\Psi$ (2S)</td>
<td>$3685.00\pm 0.12$</td>
<td>$3.3\cdot 10^{-5}$</td>
<td>OLYA</td>
<td>1979-1980</td>
</tr>
<tr>
<td>$\Upsilon$</td>
<td>$9460.57\pm 0.09\pm 0.05$</td>
<td>$1.2\cdot 10^{-5}$</td>
<td>MD-1</td>
<td>1983-1985</td>
</tr>
<tr>
<td>$\Upsilon'$</td>
<td>$10023.5\pm 0.5$</td>
<td>$5.0\cdot 10^{-5}$</td>
<td>MD-1</td>
<td>1983-1985</td>
</tr>
<tr>
<td>$\Upsilon''$</td>
<td>$10355.2\pm 0.5$</td>
<td>$4.8\cdot 10^{-5}$</td>
<td>MD-1</td>
<td>1983-1985</td>
</tr>
<tr>
<td>$J/\psi$</td>
<td>$3096.917\pm 0.010\pm 0.007$</td>
<td>$3.5\cdot 10^{-6}$</td>
<td>KEDR</td>
<td>2002-2008</td>
</tr>
<tr>
<td>$\Psi$ (2S)</td>
<td>$3686.114\pm 0.006\pm 0.010$</td>
<td>$2.0\cdot 10^{-6}$</td>
<td>KEDR</td>
<td>2013</td>
</tr>
<tr>
<td>$\psi(3770)$</td>
<td>$3772.9\pm 0.5\pm 0.6$</td>
<td>$2.1\cdot 10^{-4}$</td>
<td>KEDR</td>
<td>2002-2006</td>
</tr>
<tr>
<td>$D^0$</td>
<td>$1865.43\pm 0.60\pm 0.38$</td>
<td>$3.8\cdot 10^{-4}$</td>
<td>KEDR</td>
<td>2002-2005</td>
</tr>
<tr>
<td>$D^+$</td>
<td>$1863.39\pm 0.45\pm 0.29$</td>
<td>$2.9\cdot 10^{-4}$</td>
<td>KEDR</td>
<td>2002-2005</td>
</tr>
<tr>
<td>$\tau$</td>
<td>$1776.69_{-0.19}^{+0.17} \pm 0.15$</td>
<td>$1.3\cdot 10^{-4}$</td>
<td>KEDR</td>
<td>2005-2008</td>
</tr>
</tbody>
</table>

**Why mass measurement?**

- Fundamental parameter
- Test of theoretical models
- Bench mark on the mass scale of elementary particles
- Bench mark on the energy scale of a given collider ($J/\psi$, $\psi$(2s) masses used in BEPC-II $\tau$- lepton mass experiment)
- Absolute calibration of momentum measurements in detector tracking systems

KEDR $J/\psi$, $\psi$(2S): in order improved as compared with OLYA
Recent results

Recent papers on the VEPP-4 HEP activity:

- High precision particle mass measurements using the KEDR detector at the VEPP-4M collider (In Russian). Uspekhi Fizicheskikh Nauk 184(1) 75-88(2014)
- Results of measurement of psi(3770) parameters at KEDR/VEPP-4M. (In Russian) Yadernaya Fizika, 76(2013)92-97

The following experiments are planned for 2014:
- scanning at energy 2E = 3.1-4.0 GeV for the measurement of R
- collection of statistical data at the peak of the ψ (3770) meson to measure the mass D_mesons

The ratio of the electron and muon widths of the J/ψ meson has been measured using direct J/ψ decays. The measurement result Γ_{ee}/Γ_{μ+μ} is in a good agreement with the lepton universality.

The compilation of the results on ψ(2S) mass. Relative accuracy of the KEDR result is about 2*10^{-6}.
SR experiments at VEPP-3

0a – LIGA and X-ray lithography
0b – “Explosion”
2 – Precision diffractometry and anomalous scattering
3 – X-ray fluorescence analysis
4 – High-pressure diffractometry
5a – X-ray microscopy and micro-tomography
5b – Time-resolution diffractometry
5c – Small-angle X-ray scattering
6 – Time-resolution luminescence
7 – SR beam stabilization
8 – EXAFS spectroscopy
10 – Metrology/EXAFS in soft X-ray

http://ssrc.inp.nsk.su/conf/SR2014
SR experiments at VEPP-4

New SR experimental hall at VEPP-4

7-pole electromagnet wiggler
Installed recently at VEPP-4

New experimental station for fast processes study

Beam lines in the VEPP-4 SR experimental hall
SR experiments at VEPP-4

Study the fast processes proceeding in a detonation wave, at the front of a shock wave

Experimental setup for density distribution reconstruction.

1-Gas X-ray detector DIMAX, 2 - explosive 3 – SR

Shock front is measured in a single pulse

Turn by turn measuring the density distribution in shock
Recorded up to 500 frames
The Talbot interferometer, created at VEPP-4M and used for solving problems of a computer X-ray tomography and microscopy, opens up possibilities for research in such science fields as: geology, materials technology, archeology, biology and are especially important for medical research.

(a) – Absorption contrast,
(b) – Tomographically reconstructed three-dimensional structure of a strawberry from a set of phase projections.

Small low-contrast details, such as a stalk, leaves and seeds which are not distinguishable at absorption contrast are well visible.
The electro-nuclear experiments with internal targets at the electron-positron storage ring VEPP – 3 have been performed by BINP for several years. During this time the data on the tensor analyzing power in reactions with deuteron have been obtained, the two-photon exchange contribution in (ep) -scattering have been measured. Further progress of experiments is connected with introduction into VEPP-3 a quasi-real photon tagging system, which will allow performance of a series of measurements of the polarization observables in various reactions with photon energy of up to 1.5 GeV.

In 2013 the tagging system was introduced into VEPP-3 ring and tested with electron and positron beams. The spectra of the bremsstrahlung and the annihilation radiation were detected at zero angle of the tagging system.
Energy stability

Spring dissolution front runs to tunnel walls

Processing of energy data with “predication function” in J/Psi run

Long term (hours) stability $10^{-6}$ allow one to find optimal parameter for the measurement. High-frequency pulsation (up to 5 Hz) lead to broadening of resonance spin precession frequency. This effect increases statistical error of the experiment.

Thrice-repeated partial depolarization

Correlation of daily energy oscillations with mean orbit radius deviations

All three measured energy values are in the 6 keV interval $(3 \times 10^{-6})$ due to guide field drift

In the precision measurements of the mesons masses resonance depolarization method was used for beam energy calibration with accuracy $10^{-6}$. An energy drift $10^{-4}$ was critical for thous experiments therefor NMR data of guiding magnetic field measurement and temperatures of magnets, tunnel and cooling water were used for beam energy reconstruction between energy calibrations. Accuracy achieved $(3 - 10) \times 10^{-6}$ was enough for thouse experiments.

But at VEPP-4M another experiment of CPT-invariance test by comparison of spin precession frequencies of electron and positron simultaneously circulating in VEPP-4M storage ring with accuracy $10^{-8}$ is planned. The error of this experiment directly depends on stability of guiding magnetic field therefore long term stability and field pulsation are the great of importance.

Long term (hours) stability $10^{-6}$ allow one to find optimal parameter for the measurement. High-frequency pulsation (up to 5 Hz) lead to broadening of resonance spin precession frequency. This effect increases statistical error of the experiment.
GUIDING FIELD STABILIZATION SYSTEM

NMR-based system

Induction method

The essence of the method is measuring the field ripples by the induction sensor to adjust the current in the magnet with the help of parallel connected to IST current generator, which is opposite to the measured ripples.

The graph shows that at a frequency of 5 Hz suppression of ripples is more than by 10 times, at a frequency of 10 Hz - 3 times, at a frequency of 30 Hz - 2 times.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
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<tr>
<td>Field measurement error</td>
<td>&lt; 0.5·10⁻⁶</td>
</tr>
<tr>
<td>System bandwidth</td>
<td>0.1 Hz</td>
</tr>
<tr>
<td>Range of the field deviation</td>
<td>±10⁻⁴</td>
</tr>
<tr>
<td>Field variation with the feedback loop closed</td>
<td>2·10⁻⁶</td>
</tr>
<tr>
<td>System bandwidth</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Range of the field deviation</td>
<td>±2·10⁻⁴</td>
</tr>
<tr>
<td>Field variation with the feedback loop closed</td>
<td>4·10⁻⁷</td>
</tr>
</tbody>
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A. Pavlenko et. al. METHOD OF BROADBAND STABILIZATION OF THE VEPP-4 MAIN FIELD. Poster session A, October 07
Comparison of e+ and e- beam energies

Distinct-in-time comparison:
measured beam energy in series of consecutive calibrations of e+ and e- with electrostatic orbit bumps ON
Ep - Ee = 2.3 ± 2.6 keV
Reason of difference:
electrostatic orbit separation in 4 IPs

“Nano-resolution”:
scan rate = 2.5 eV/s
relative error ~ 2*10^-9
RF separation of colliding beams at the technical section

**Goal**: to exclude contribution ($\sim 10^{-6}$) of electrostatic orbit separator influence to systematic error in CPT test experiment based on comparison of spin frequencies of electron and positron.

**Principle scheme**

$$X = \frac{\chi \beta}{2 \sin 2 \pi \nu_x} \cdot (\cos 2 \pi \nu_x - 1)$$

**Design two-turn closed orbit**

**Beam-beam simulation**

Distribution in plane of betatron amplitudes at various values of orbit separation in TS

**BPM data with 2 e\textsuperscript{-} bunches**

**1e\textsuperscript{-}x1e\textsuperscript{+} bunches separation test**

Some first experimental data of the RF separation system test in the end of 2012-begin of 2013
Increase in VEPP-4M luminosity at low energy

In 2014, we performed an experiment in order to increase the luminosity of the collider VEPP-4M at a low energy (<2 GeV).

### Luminosity formulae (flat beam)

\[
L = \frac{\gamma l \xi_y}{2e \beta_y}, \quad \xi_x = \frac{N_r \beta_x^*}{2\pi \sigma_x^2}, \quad \xi_y = \frac{N_r \beta_y^*}{2\pi \sigma_y \sigma_x^*}.
\]

Monochromatization parameter

\[
\lambda_m = \frac{\sigma_{xx}}{\sigma_{y\beta}}, \quad \sigma_x = \sqrt{\sigma_{x\beta}^2 + \sigma_{xx}^2}, \quad \sigma_y = \sigma_{y\beta} \sqrt{1 + \lambda_m^2}
\]

\[x = x_{\beta} + \eta_s \frac{\Delta E}{E}\]

### BB Footprint

- Red → betatron resonance up to 6th order
- Blue → synchro–betatron satellites

### Distribution in betatron amplitude plane

- \(I_p=3.0 \, mA, \beta_x=65 \text{cm}, \xi_y=0.036\)
- \(I_p=5.0 \, mA, \beta_x=32.5 \text{cm}, \xi_y=0.053\)

**IP with dispersion**

Increase in \(\lambda_m\) owing to reducing \(\beta_x\) (not \(\varepsilon_x\) – emittance!) results in:

- Increase of critical current due to decrease of \(\xi_x\)
- Increase of critical \(\xi_y\) because of coupling resonance suppression

### VEPP-4M base structure

- With beta_x in IP reduced by half

The result of the experiment

After double decrease of \(\beta_x\) resulted in increasing of a threshold current by half, accompanied by \(\beta_x\) beating at the ring though. After studying the problem, experiments will be continued.
Summary

• Since 2002 VEPP-4 collider with detector KEDR provides world-class results for HEP community

• Many other experimental programs (SR, nuclear physics, test beam, accelerator physics study, etc.) are successfully performed at the accelerator facility

Plans for the coming two years:
• Scanning at energy $2E = 3.1-4.0$ GeV for the measurement of $R$
• Collection of statistical data at the peak of the $\psi (3770)$ meson to measure the mass $D_{mesons}$
Co-authors

Thank you for your attention!