e+e- COLLIDER VEPP-4M: STATUS AND PROSPECTS

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Abstract

VEPP-4M is an electron-positron collider operating in the wide beam energy range from 0.9 GeV to 5.5 GeV. Since 2002 experiments on HEP are conducted at the collider with detector KEDR. Besides HEP, there are other scientific programs at the VEPP-4 accelerator complex including SR experiments, nuclear physics studies with internal gas target, CPT-theorem verification, accelerator physics experiments, etc. The paper discusses the recent results, present status and prospective plans of the facility.

INTRODUCTION

Starting from 2002 experiments are carried out with the universal magnetic detector KEDR [2] at the electron-positron collider VEPP-4M [3]. The VEPP-4M collider consists of the booster ring VEPP-3 with energy from 350 MeV to 2000 MeV and the main ring operating in the beam energy range from 0.9 GeV to 5.5 GeV. The physics program of the detector is focused on the study of ψ-, Υ-mesons and $\gamma\gamma$-physics. Precise mass measurements of J/ψ, ψ(2s), ψ(3770), D mesons and τ lepton were the goal of the first series of the experiments. Also electron partial width for J/ψ and ψ'-mesons were measured.

Table 1: Main Parameters of VEPP-4M.

Parameters	Values	Units
Circumference	366	m
Bending radius	34.5	m
Tunes Q_H/Q_V	8.54/7.58	
Mom. compaction	0.017	
Max. energy	5.5	GeV
Nat. chromaticity C_H/C_V	-13/-20	
RF-frequency	181.8	MHz
Harmonic number	222	
RF power	0.3	MW
RF voltage	5	MV
No.of bunches per beam	2	

The resonant depolarization (RD) technique [4] was used for precise instantaneous energy calibration. Continuous energy measurements were performed by determination of the utmost energy of the γ-quanta obtained from the Compton backscattering of laser photons against the electron beam [5, 6]. Main parameters of VEPP-4M are given in Table 1. The layout of the complex is shown in Fig.1.

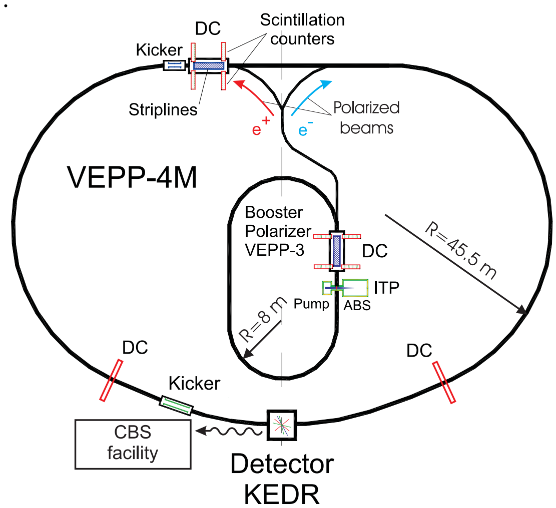

Fig.1: The VEPP-4 layout with main HEP experimental set-up: detector KEDR, Compton backscattering (CBS) system, gas internal target (ITP), counters (DC) and kickers for precise polarization experiments.

Besides the particles physics, there are other various experimental programs at VEPP-4 including studies with the synchrotron light, nuclear physics with polarized/unpolarized internal gas target, extracted test beam of e- or γ for methodical goals, etc.

As the scientific program initially planned at 2000 for the decade is close to completion, it is good time for discussion of the results obtained and future plans.

HEP PROGRAM

In spite of rather moderate luminosity of the collider we were able to conduct experiments providing interesting and actual results due to the following factors:

- Wide beam energy span available for experiments that extends from 0.9 GeV to 5.5 GeV;
- The record-breaking accuracy (~10^{-6}) beam energy calibration that was developed at VEPP-4M with the help of the RD technique invented at BINP in the past;
- On-line monitoring of the beam energy during the luminosity run by Compton backscattering of the laser photons (accuracy is ~$3\cdot10^{-5}$);
- Universal magnetic detector KEDR with *LKr* calorimeter and Cherenkov aerogel counters with characteristics comparable with the best detectors in the world.

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Fig.2 depicts a long time stability run when the energy was measured directly by RD, CBS and determined with the NMR probe inserted in the main dipole field.

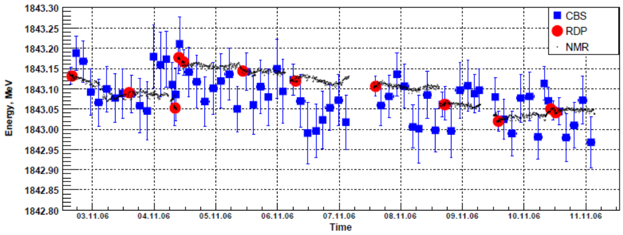

Fig.2: RD, CBS and NMR calibration of the VEPP-4M beam energy.

Table 2 lists the particles from the Particle Data Group booklet with the most precisely measured masses and two of them (J/ψ and ψ') were defined at VEPP-4M.

Table 2: Accuracy of the particle mass measurement

Particle	$\Delta M/M$ (PDG)
p	$0.1\cdot10^{-6}$
n	$0.1\cdot10^{-6}$
e	$0.1\cdot10^{-6}$
m	$0.1\cdot10^{-6}$
$\pi^{\pm}$	$2.5\cdot10^{-6}$
ψ'	$3.0\cdot10^{-6}$
J/ψ	$3.5\cdot10^{-6}$
π^0	$4.5\cdot10^{-6}$

Besides the ψ-mesons, the mass of the τ lepton was determined at VEPP-4M with the world record precision:

$$M_\tau = 1776.81^{+0.25}_{-0.23} \pm 0.15 \text{ MeV}$$

Other recent HEP results from VEPP-4M/KEDR include D^0- and $D^{\pm}$- mesons mass measurement, search for narrow resonances in e^+e^- annihilation in the beam energy interval 0.92 GeV-1.55 GeV, study of $\psi(3770)$, $\psi(2s)$, η_c and many more experiments presented in detail in [7-12].

The next experimental run will relate to the VEPP-4M operation with the energy increase, measurement of the hadron cross-section and $\gamma\gamma$-physics. In order to prepare for the run, in 2011 we tested the collider operation with energy ramp up to 4 GeV. The main goal was to check performance of all the accelerator systems (PS, SR absorbers, magnet cooling, etc.) with higher electrical/radiation power and tune the beam parameters for optimal luminosity, beam lifetime, etc. Fig.3 shows the testing run log and the luminosity obtained.

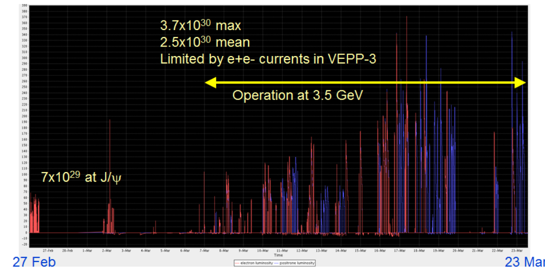

Fig.3: VEPP-4M test run at 3.5 GeV. On the left side of the plot (end of February 2011) the low energy luminosity is shown.

The collider performance increase at high energy is provided by development of the transverse and longitudinal feedback systems installed at VEPP-4M and suppressing the collective instabilities. Fig.4 depicts the e^- beam current during the test run.

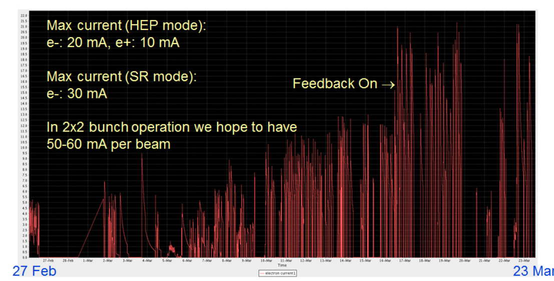

Fig.4: Electron current in VEPP-4M; a feedback system ON increases the maximum achievable current.

NUCLEAR PHYSICS

For many years nuclear physics experiments at VEPP-3 with internal gas target (proton or deuteron, polarized or unpolarized) have been carried out [13]. Advantages of our installation include easy change of the beam energy, relatively high current (up to 150 mA of e^-), precise beam energy calibration (CBS technique is applied also at VEPP-3), using of e^+e^- beams in the same geometry (both rotate anti-clockwise).

The recent experiments were dedicated to the proton form factor study. In the late ninetieth it was found that measurement result of the proton electric and magnetic form factor by elastic e^- scattering depends on whether the electron beam is polarized or not. It is explained now by contribution of the two-photon processes in the scattering. As this contribution depends on the electron charge, there is a possibility to estimate the two-photon contribution experimentally by comparison of e^+p and e^-p scattering. At VEPP-3 such experiment was performed initially in 2009 and continued in 2011 according to a modified kinematic scheme. During the run either e^+ or e^- beam is injected and accelerated in VEPP-3, and its elastic scattering at the hydrogen target is registered by a detector. After 15-20 min of the data collection, the beam

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charge is changed. Fig.5 shows the beam charge integral collection.

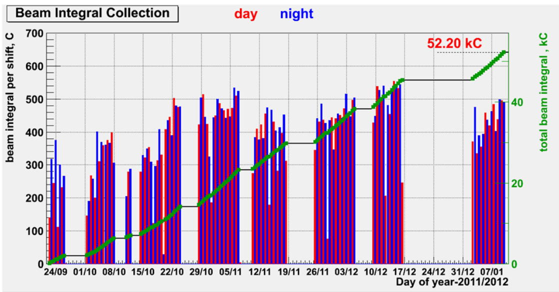

Fig.5: The beam integral collection in (e^+p/e^-p) scattering at VEPP-3.

The experimental data processing is presently under way; Fig.6 shows the time-of-flight analysis of the detected particles.

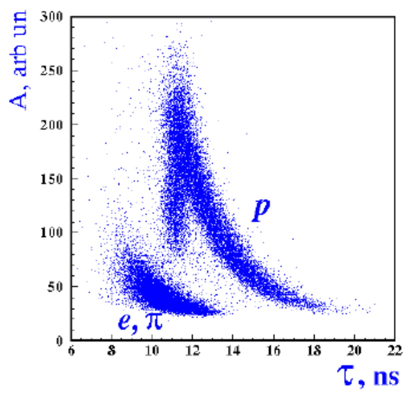

Fig.6: Escaped protons resolution by the time-of-flight measurement.

EXTRACTED TEST BEAM

To calibrate HEP detectors components, electron or γ beams with well-defined properties are used. In 2010 new experimental facility aimed for this purpose was developed at VEPP-4M. High energy electrons circulating in the accelerator collide either with residual gas atoms or with a specially inserted tungsten target and produce a flux of hard γ rays, which can be used directly or be converted to the electron/positron beams [14].

The experimental hall equipped with collimators, magnet spectrometer and detectors is shown in Fig.7. Parameters of the test γ or e^- beams are given in Table 3.

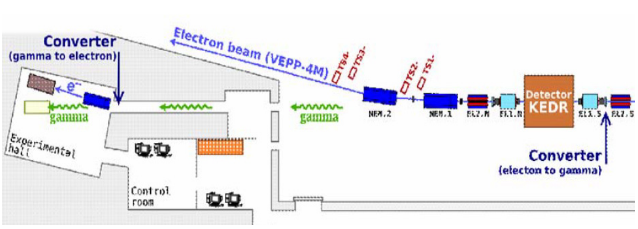

Fig.7: Test beam facility at VEPP-4M.

The realized experimental set-up allowed us to observe and measure, for the first time in Russia, focusing of the Cherenkov radiation from a four-layer aerogel with refraction index changing from layer to layer (Fig.8).

Table 3: Test beams parameters

	e^-	γ
E, GeV	0.1 ÷3.0	0.1 ÷3.0
σ_E/E, %	0.5 ÷5.0	~ 1
Intensity, Hz	10 ÷1000	1000
Resolution, mm	0.5	-

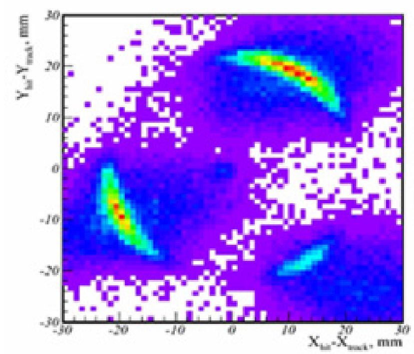

Fig.8: A Cherenkov-light ring observed at the VEPP-4M test beam facility

Width of the focused Cherenkov-light ring (~1 mm) corresponds well to that theoretically predicted.

Besides, scintillating crystals for detector for the COMET experiment (JPark, Japan) were calibrated at the test beam bench in 2011.

SR EXPERIMENTS

Experiments with synchrotron light have been carried out at VEPP-3 for more than 30 years. Twelve stations are installed in the experimental hall providing study on X-ray lithography, high pressure and time resolving diffractometry, EXAFS, X-ray fluorescence analysis, X-ray microscopy, small-angle scattering and others. One beam line is intended for stabilizing of the SR ray through a feedback between light monitors and VEPP-3 steering magnets. For details of numerous results we refer to [15].

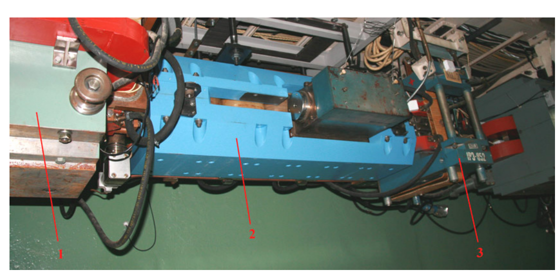

Fig.9: New wiggler installed at VEPP-4M.

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Few years ago experiments in a new hall of VEPP-4M were started. In 2011 a 7-pole electromagnetic wiggler was installed at VEPP-4M (Fig.9) to enhance the radiation flux almost by one order of magnitude as compared to the bending magnet radiation used before. As the wiggler magnetic field exceeds the field in the bend, the radiation wavelength decreases. These facts allow starting a new program on extremely fast time resolution experiments with different explosive materials.

ACCELERATOR PHYSICS

Advanced beam diagnostics and other unique equipment (single-turn kickers/pick ups, Touschek polarimeter, nonlinear magnets, etc.) allow us to perform different studies in the area of accelerator science and technique. Due to the lack of space I can mention here only few of them.

Precise Polarization Experiments

A new system for extremely precise measurement of the beam polarization degree based on a Touschek electron pairs registration was recently applied at VEPP-4M. Number of counters installed in the ring vacuum chamber increases the registration efficiency by factor 10 as compared to the previous set-up. The count rate for the scattered electrons is now 1.5 – 2.0 MHz for 2 mA beam current. An absolute record accuracy ($1.5 \cdot 10^{-9}$) of the measurement of depolarization frequency is achieved. We hope that this feature will open new horizons for the energy calibration experiments. Another interesting application is a *CPT* theorem proving by comparison of the e^+/e^- spin precession frequency. Earlier such experiments were carried-out in BINP at VEPP-4M collider and now we hope to improve the spin frequency resolution up to 10^{-8}.

Fig.10 shows the process of a slow depolarization of electrons due to the extremely precise scanning of a depolarizer frequency with the rate corresponding to the energy shift of 2.5 eV/s.

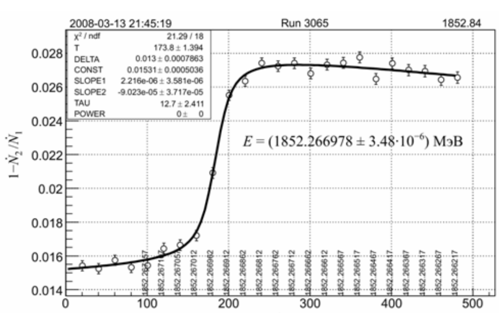

Fig.10: Nano-scale resolution of the energy measurement

Bunch Rotation in Longitudinal Phase Space

Generation of the ultra-short electron bunches in storage rings (for *ps*-time-resolving SR spectroscopy, laser-plasma acceleration experiments, etc.) is discussed extensively. Our experiment was based on the method described in [16], when the beam rotates vertically due to the coupling of the vertical/synchrotron motion under the short coherent kick. A large enough positive chromaticity (in our case – vertical) should be applied to the beam. The experimental study relates to the question: if natural decoherence allows us to see the beam tilt at all? Fig.11 (left) shows the BPM signal as a function of the turn number while the right plot corresponds to the beam tilt in the $y - s$ plane. The vertical chromaticity was set as +5 in this measurement.

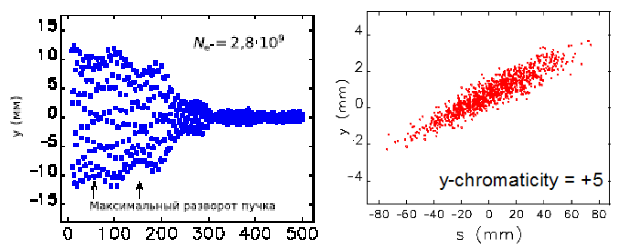

Fig.11: The bunch tilt and decoherence after the vertical kick. Arrows in the left plot show the moment of maximum beam tilt (~ half of synchrotron oscillation).

Experiment has shown [17] that at VEPP-4 this method works for I_{bunch} < 1 mA ($N < 10^{10}$ particles). For more intense beams decoherence of betatron oscillations due to head-tail interaction becomes important.

Resonance Crossing Observation

Turn-by-turn BPMs measuring the beam centre-of-charge evolution became a routine diagnostic instrument at circular accelerators many years ago. At VEPP-4M we have recently developed a unique synchrotron light monitor allowing observation of the transverse beam profile turn-by-turn during 2^{17} revolutions. The Fast Profile Meter is based on a Hamamatsu R5900U-00-L16 Multi-Anode Photomultiplier Tube with single anode size of 0.8 mm [18]. As an example of the new device potential the results of the nonlinear resonance crossing as a function of time are shown in Fig.12.

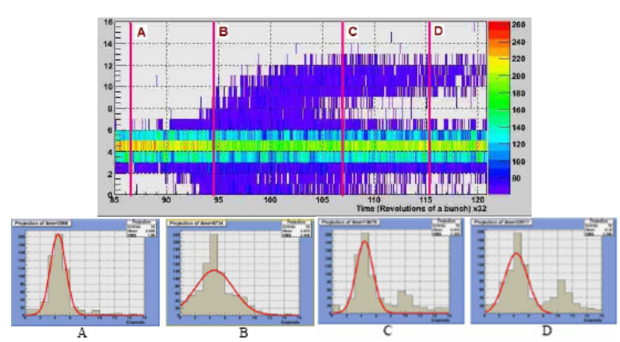

Fig.12: The resonance crossing experiment. Upper plot shows creation of a stable resonance island and particles trapping. Lower plot shows the beam profile evolution; a moment of the particle trapping in the island is clearly seen.

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FUTURE PLANS AND PROSPECTS

The HEP program at the collider VEPP-4M formulated for a decade in 2000 by the BINP scientific community is almost over. The last remaining item from that list is experiment with energy increase up to 4.5 GeV – 5 GeV, which relate to measurement of the hadron cross-section *R* in the wide energy range and $\gamma\gamma$-physics. We are expecting that this experiment will be completed in 2-3 years. The question arises: what kind of future studies can be carried out at our facility afterwards? The answer is not simple but one point is clear for us: experimental programs planning at VEPP-4M must be challenging, interesting and satisfy prospective demands of relevant scientific communities. Among such plans I will mention here very briefly the following ones:

- Longitudinally polarized e^+e^- beams and HEP experiments with them. Future super-factories (SuperB in Italy, SuperCτ in Novosibirsk, etc.) will essentially apply longitudinally polarized e^+e^- beams. But the world experience on operation with such beams is very poor so production and study of longitudinally polarized electrons and positrons in circular colliders look rather attractive and actual. A strong point of the VEPP-4 complex is a possibility to polarize the beams in VEPP-3 in a reasonable time (~30 min).
- Converting of VEPP-4M in SR source. Several scenarios are now under consideration starting from moderate modernization of the storage ring (say, just insertion of modern wigglers and undulators) to the deep reconstruction when all magnets and vacuum components are replaced by new ones. In the last case a preliminary study [19] has shown that one may have 1 nm horizontal emittance at 3 GeV beam energy and 250 mA current.
- A new e^+e^- collider in the VEPP-4M tunnel is now under exploration. The project (with preliminary name Super *K*-meson Factory) is based on the Crab Waist collision scheme [20] and is considered as a prototype of the Super Cτ Factory. The double-ring collider allows us to have the peak luminosity from 10^{34} cm^{-2}s^{-1} at the ϕ-meson energy (0.5 GeV per beam) to 5×10^{34} cm^{-2}s^{-1} at the ψ-meson energy (1.55 GeV per beam).

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