The VEPP-4M Collider Operation in the Experiment of Precise Tau-lepton Mass Measurement

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Abstract

In 2004-2006, the principal high-energy physics experiment carried out at the VEPP-4M electron-positron collider was precise measurement of the τ-lepton mass. This experiment requires reliable and coordinated operation of all the facilities: the injector, the booster storage ring VEPP-3, the beam transport lines, the VEPP-4M collider, and the KEDR detector. To provide high performance, both intensive work of well-qualified operators and high automatization of the machine control are required. The operation scheme and the most important results are described.

HIGH-ENERGY PHYSICS EXPERIMENTS

The VEPP-4 is a multipurpose accelerating-storage complex [1]. It includes the VEPP-4M electron-positron collider (6 GeV maximal beam energy), the VEPP-3 booster storage ring (2 GeV), and the Injector (350 MeV) composed of an electron beam source, linear accelerator, electron-to-positron converter and the booster synchrotron.

Since 2004, the VEPP-4M collider is operating for high-energy physics (HEP) experiments in the 1.5-2.0 GeV beam energy range. The most principal of them is precise measurement of the τ-lepton mass at the production threshold [2]. Exact value of the τ-lepton mass is required to verify the lepton universality principle which is one of the postulates of the Standard Model, the most complete theory describing fundamental properties of matter. At present, measurement accuracy reached in this experiment is the best in the world.

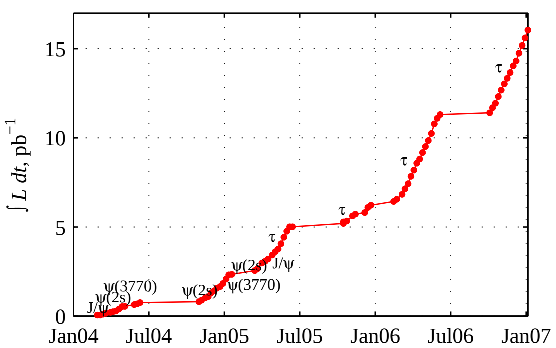

Figure 1: Luminosity integral 2004-2006.

A series of experiments to measure masses of the J/ψ, ψ(2s) and ψ(3770) mesons has been also performed [3]. The data measured specify an energy scale in the range around 3 GeV which is a basis for accurate determination of masses of all charmed particles. Measurement accuracy reached in these experiments is 2 times better than the world average value for ψ(2s), and 3 times better for ψ(3770). In high-energy physics, masses of only 5 particles (e, p, n, μ, π) have been measured with better accuracy.

In order to measure masses of particles with extremely high precision, a method of absolute beam energy calibration is realized using the resonant depolarization technique [4]. A world-record 10^{-6} relative accuracy of beam energy measurement has been achieved.

Fine adjustment of the accelerator parameters and improving of the machine reliability, result in gradual increase of average luminosity. The luminosity integral collected in 2004-2006 is shown in Figure 1, one can see gradual rise of the derivative.

In addition to high-energy physics, scientific research and advanced technology development are also performed using synchrotron radiation at the VEPP-3 and VEPP-4M storage rings. Principal subjects are: material science, detonation study, chemistry, geology, archaeology, biomedicine, nanotechnology, etc.

OPERATION TIME DISTRIBUTION

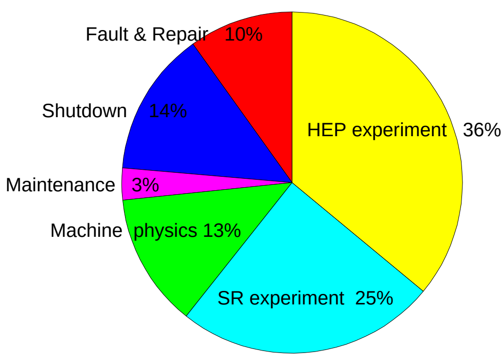

Figure 2: Operation time distribution.

Figure 2 shows average distribution of operation time of the VEPP-4 accelerating-storage complex in 2004-2006. As one can see, total operation time is mainly divided between two experimental programs: high-energy physics (36%) and synchrotron radiation (25%). Machine physics shifts (13%) are used both to keep the machines in operating condition required for the experiments and to perform investigations on beam dynamics and accelerator physics. Regular maintenance works (3%) are executed every week usually Monday morning. Shutdown time (14%) is formed mainly by summer vacation period and used for upgrade and maintenance of the accelerators, particle detector, and support systems (incoming power supplies, water cooling system, etc). Quite a big time loss caused by various equipment faults (10%) may be accounted for multiplicity, complexity, and, primarily, age of the equipment.

To analyze and prevent a fault, more than 1500 beam and accelerator parameters are recorded permanently in a database. 1-second samples are available during last 24 hours, 30-second samples are stored for 1 year, older data are relocated to an archive storage.

Distribution of the working time loss in 2003-2004 season (September-July) is presented in Figure 3. A quarter

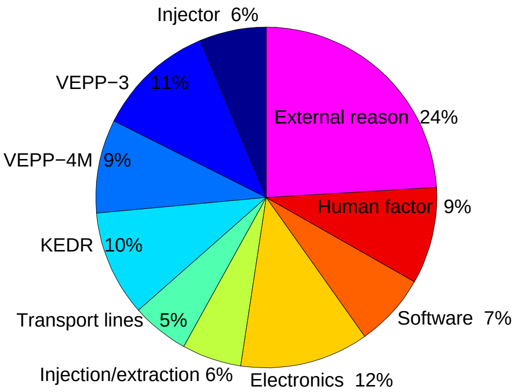

Figure 3: Working time loss.

(24%) of the total time loss results from external reasons such as incoming power failure, cooling water overheat or leakage, vacuum deterioration, impure working gas of the KEDR drift chamber, etc. Failures percentage of the individual facilities is in the 5-10% range: Injector 6%, VEPP-3 11%, VEPP-4M 9%, KEDR 10%, beam transport lines 5%, and high-voltage beam injection/extraction systems 6%. These values include failures of magnet systems, RF systems, beam diagnostic instruments, beam energy measurement systems, etc. Because there is no evident leader in this group, one can conclude that reliability of these facilities is almost equal.

Electronics part (12%) means failures of the control system hardware as a whole including control computers, CAMAC electronics, low-power circuitry of the magnet power supplies and RF systems. Together with the software part (7%) including both system and application software, contribution of the control system is quite big. One of the main reasons is a wide range of different-type and different-aged electronic devices and computer codes used for the operation.

Human factor (9%) is not really so bad as it seems at first glance, because it includes not only operator errors but also unavoidable time expenses for operators training. We have to do this training on-the-run, because there is no time specially assigned for this important process.

WORKING CYCLE AUTOMATION

In a HEP experiment, the KEDR data collection period is determined by lifetime of the electron and positron beams colliding in the VEPP-4M in 2×2-bunch mode. During the data collection, two electron or positron bunches are accumulated in the VEPP-3 booster storage ring. Accumulating rate of positrons is $30-50$ μA/sec (dependent on accumulated current) whereas for electrons it is about 2 mA/sec. In $1.5-2$ GeV energy range, a bunch current in the VEPP-4M is limited by beam-beam effects and does not exceed 3 mA. Taking into account the perimeter ratio $\frac{P_{\mathrm{VEPP-4M}}}{P_{\mathrm{VEPP-3}}} \simeq 5$, $10-15\%$ beam loss during acceleration in the VEPP-3, and $70-90\%$ injection efficiency, two bunches of 20 mA each should be accumulated in the VEPP-3.

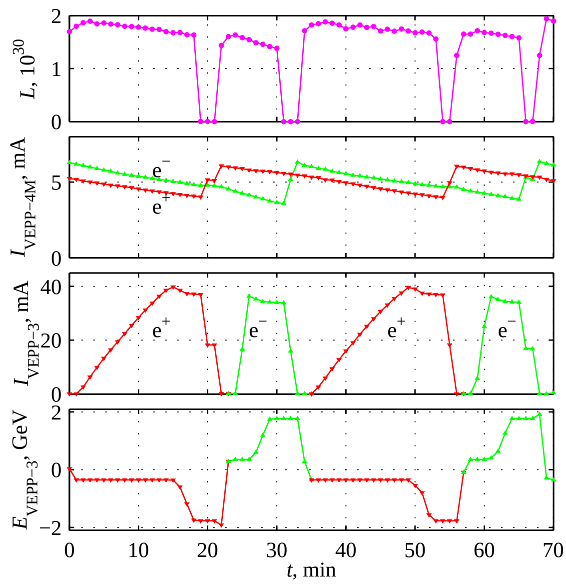

Figure 4: Working cycle.

Figure 4 shows (top-down) the luminosity, the VEPP-4M electron and positron current, the VEPP-3 beam current and energy during a typical experimental run. The working cycle includes: accumulation of positrons in the VEPP-3 ($15-20$ minutes), acceleration up to the extraction energy (5 minutes), bunch-by-bunch extraction and injection into the VEPP-4M, magnetic cycle and polarity change of the VEPP-3 and Injector (5 minutes), electron accumulation ($1-2$ minute), acceleration and injection into the VEPP-4M. Total time required to refill beams in the VEPP-4M is $30-40$ minutes. Note that the VEPP-4M electron and positron beams should be separated in the interaction point during injection, because strong beam perturbation in colliding mode leads to beam loss.

At the beginning of HEP experiments with the KEDR detector, all these processes were controlled manually by an operator. Furthermore, current-dependent betatron tune shift and time-spaced injection of electron and positron beams results in a drift of the optimal combination of the VEPP-4M parameters tuned for maximal luminosity. To optimize the luminosity, an operator should control permanently a set of parameters such as betatron tunes, coupling of betatron oscillations, matching of beam position in the interaction point, etc.

From the operation experience, an automation procedure has been developed. An artificial intelligence element called "autopilot" is supplemented to the control system as an additional highest level. The "autopilot" acquires a set of beam and accelerator parameters, performs data processing and generates a proper command set for the control software. Working conditions are set by an operator in a configuration file. The "autopilot" performs all the operations required for luminosity optimization and beam injection. This automation procedure has been found very useful for operators. Moreover, it also helps to equalize shift efficiency of both experienced operators and beginners, as it is illustrated by Figure 5 showing luminosity averaged over all shifts of the 2005-2006 working season for each operator.

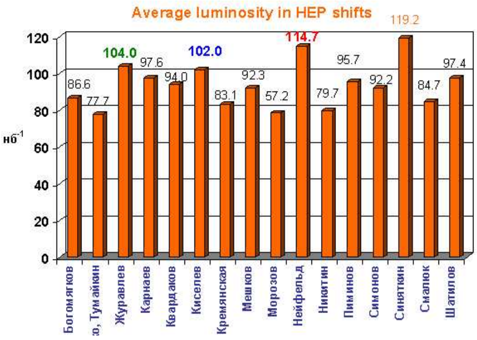

Figure 5: Average luminosity in shifts.

Certainly, this automation works only if there is no any fault. Besides, an important procedure performed manually is the beam energy calibration by resonant depolarization method. We did not managed yet to introduce reliable automation into this procedure due to its complexity and high significance for precise measurement of particle masses.

PERFORMANCE IMPROVEMENT

One of peculiarities of the HEP experiments realized at the VEPP-4M is the high-precision beam energy evaluation. To estimate the beam energy between absolute calibrations by the resonance depolarization method, an empirical formula is used. This formula provides 20 keV accuracy of energy interpolation using the dipole magnetic field and temperature of the magnets, tunnel walls, cooling water, etc. On-line monitoring of the magnetic field with 10^{-6} accuracy is realized by the nuclear magnetic resonance method. For the temperature monitoring, a new system has been developed [5]. This system is based on high-precision digital temperature sensors with the resolution of $0.0625°$C and absolute accuracy of $0.5°$C in the $0 \div 70°$C temperature range. A computer code is implemented into the control system to read, store in a database and visualize data of about 300 temperature sensors installed.

Continuous temperature monitoring shows considerable diurnal and seasonal variations of the VEPP-4M magnets temperature, which cause beam energy variation up to $80\ \mathrm{keV}/°\mathrm{C}$.

For the VEPP-4M magnets, a double-loop water cooling system is used. The magnets are cooled by circulating distillate which is cooled by service water in a heat exchanger. Temperature of the service water depends on many external factors such as ambient temperature, atmospheric humidity, cooling condition in a cooling tower, etc. To stabilize temperature of the VEPP-4M magnets, a system of distillate thermal stabilization has been developed. The service water flow in the heat exchanger, and therefore the heat-transfer rate, is regulated by a computer-controlled valve. Temperature of the distillate and service water measured at the heat exchanger input and output is used for the valve control. The thermal stabilization system keeps the distillate temperature stable within 0.1 degree range while the service water temperature has 5-degree variation.

During the HEP experiments, one of the principal efficiency decreasing factors is a longitudinal beam instability, which occurs due to parasitic high-order modes (HOM) of the VEPP-4M RF cavities. Fine tuning of remote-controlled HOM suppressors allows us to find stability regions of longitudinal beam motion. But the cavity thermal expansion leads to a shift of HOM conditions away from the stability regions. To stabilize the RF cavity temperature, automatic heaters of cooling water have been developed [6]. For each RF cavity, a 5 kW flowing water heater is switched on/off by controllable electronic switches. Temperature analysis and power control is provided by a microcontroller. Using of the stabilization system, temperature variation of the RF cavities have been reduced from 5°C down to 0.2°C. As a consequence, probability of excitation of the phase oscillations is reduced more than in 100 times.

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