STORAGE RING PROGRAM IN NOVOSIBIRSK

(Review)

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Activity connected with the development and construction of the storage rings and their use for experiments with colliding beams were launched in the Institute of Nuclear Physics in 1956. The first machine designed and constructed was VEP-1, the installation with electron-electron colliding beams at an energy up to 2×160 MeV. The schematic view of the machine is shown in Fig. 1. The storage ring consists of two high-vacuum circular tracks (with radius of 43 cm) with a common section where the colliding beam orbits have a tangency. The tracks were mounted one above the other. They were filled in turn with electrons fed in through the channel bifurcated near the tracks. The special ironless synchrotron at an energy of 40 MeV was used as an injector. During the filling time the orbits were spatially separated to avoid the beam-beam effects. The study of these effects due to the mutual influence of the electromagnetic fields produced by colliding beams on incoherent betatron oscillations of the electrons and the choice of the optimum operation regimes of filling and collision were the main beam behavior problems when putting the machine into operation. In addition, the effect of non-linearity in the guiding field on the beam motion and the beam behavior near the non-linear resonance were carefully investigated. The coherent phase instability of bunches was found and mainly understood. Some other features of the beam behavior in a storage ring, such as the effect of electron scattering within the bunch, the effect of ion accumulation in the beam, etc., were also studied. The maximum current value ever stored in one beam was of 0.5 A (3×10^{10} electrons). The effective two-beam operation was successfully performed with currents up to 2×100 mA at high energy. However, the usual experimental runs even at high energy were effected at currents of 2×50 mA. The pumping system of the storage ring was rather primitive; this is why the experimental run lasted usually about 10 minutes and why it was necessary to restart the filling procedure. The maximum luminosity reached was of 4×10^{28} cm^{-2} sec^{-1}.

The first beam in the storage ring was obtained in 1963, the first experiment was performed in 1965, and the last one was completed in 1967. (Note that the time schedule is surprisingly close to that of the Stanford electron-electron storage rings.) In this period of time, the e-e scattering was studied (angular distribution at several energy levels) as well as the single bremsstrahlung e^-e^- $e^-e^- + \gamma$; the double bremsstrahlung e^-e^- $e^-e^- + 2\gamma$ was found and investigated.

At present the VEP-1 machine is dismounted and its storage rings are installed in the main building of our Institute as a monument.

Long before the first beam operation on VEP-1 in our Institute, design of the machine was started with electron-positron colliding beams—VEPP-2 (1959). It is shown schematically in Fig. 2. The most difficult problem was to store a sufficient amount of positrons. To this end it was necessary to obtain the highest possible current of the electron beam accelerated in and then ejected from the 250-MeV synchrotron (the record value is 1 A, 1.5 10^{11} ejected electrons per pulse). The rather high efficiency conversion system was developed to convert electrons to positrons with the use of "X" lenses. Great efforts were made for the most complete use of the storage ring phase space on the condition of weak radiation damping with positron injection energy of 120 MeV when even the small perturbations and non-linear effects proved to be essential. To reach both a high-efficient injection and an extremely low (about 10^{-4}) ratio of positrons lost per injection cycle was a particularly complicated problem.

Besides, at such a low injection energy, even at not very high currents, various high-current effects emerged such as the coherent phase instability, transverse coherent instabilities of different natures, and decrease in the beam life-time due to the positron-positron scattering within the bunch.

In addition to the effects enumerated above on the storage ring VEPP-2, the fast damping phenomenon of the transverse bunch oscillations with matched load lines (like inflectors) was detected and investigated; the effects of coherent and non-coherent interactions of colliding beams were studied; the gas desorption caused by the short wavelength synchrotron radiation was also studied and considerably overcome. Use was made of magneto-discharge titanium pumps distributed along the orbit and operated in the guide field of the storage ring, and of the radiation absorber in the form of a baked band.

The record electron current value ever reached in VEPP-2 was about 5 A (10^{12} electrons). However, the current value actually used was much lower. The main restriction was determined by the non-coherent two-beam effects. The effects caused the increase of current values greater than 100 mA to be useless (and even harmful because of decreasing life-time) even at a maximum energy when these effects were the weakest.

An attempt was made to raise the useful electron current value. The lateral dimensions of both beams were artificially maintained large enough in order to have the tune shift less than the permissible one and in order not to excite coherent oscillations. To this end, the stochastic regime was used, produced by means of multiple passing the resonance of the betatron oscillations with the external excitation. At an energy of 2×200 MeV, we succeeded in bringing the permissible current up from 10 mA to 100 mA, which was to increase the luminosity by the order of magnitude. But this study was not finished because of the machine reconstruction.

The typical procedure of the experimental run was as follows:

1. Storage of positrons at an energy of 120 MeV; 3×10^3 injection cycles; filling time lasted one hour; the stored positron current was 50 mA.
2. Bringing the energy up to 200 MeV.
3. Capture of the positron bunch from a bucket of harmonic number 1 to that of harmonic number 3 used to obtain the least bunch length at higher energies.
4. Injection of electrons (about 100 mA) into the chosen bucket of the 3rd harmonic to provide bunch collisions in the only needed collision point supplied by experimental equipment (the bunches collided in the counter point as well; at the moment the orbits and Q-values tunes of electrons and positrons were spaced to ward off the danger of beam-beam effects.

5. The subsequent bringing of the energy up to the value needed in a certain experimental run as such, comprising detection of particles produced in reactions; the run lasted each time about 5 hours.

6. As the luminosity decreased by several times, the cycle was restarted.

The maximum luminosity obtained on VEPP-2 was about 3×10^{28} cm^2 sec^{-1}; the experiments were carried out with an average luminosity of 1×10^{28} cm^2 sec^{-1}.

In the first experiment performed on VEPP-2, pion pair production was studied in the ρ-meson resonance region. The experiment was accomplished in 1967 and appeared to be the first valuable experiment with the electron-positron colliding beams.

A wide range of experiments with energy ranging from 2×300 MeV to 2×670 MeV was performed during the period from 1967 to 1970 on VEPP-2. The list of the main ones is given in Fig. 3.

In 1970 a decision was made to stop experiments on VEPP-2 and to add to the accelerator complex a new storage ring designed for the same maximum energy but raising the average luminosity of the machine by 3 orders of magnitude. Thus in this energy range, though well-studied by now, this permitted many possibilities for new and very interesting experiments. A schematic view of the resulting accelerator complex is shown in Fig. 2. Both positrons and electrons are injected through the same channel and stored in the old storage ring VEPP-2. Naturally in each cycle the particles of one sort are stacked. Then the energy is brought up to the level required by the experiment actually being performed on the storage ring (VEPP-2M), and the particles are added to those already rotating in the storage ring, additions being small enough. The AG-lattice of the storage ring is designed so that the β-function in the collision points can be tuned to a very low value down to 2 - 3 cm. Practically the limit will be determined in the course of runing of the machine.

At present the machine assembly is practically completed. Last summer the first electron injection cycles were run. The obtained efficiency of the beam transfer from VEPP-2 into VEPP-2M was close to 100 per cent. Now full-scale putting of the machine into operation has begun.

In addition to the main course of the colliding beam experiments (and perhaps in parallel with them), experiments using synchrotron radiation (viz., X-ray spectral analysis) will be performed on the storage ring VEPP-2M.

In 1966 our Institute began the design of a machine named VEPP-3 with electron-positron colliding beams at an energy of 2×3 GeV. Next year the construction was developed. The schematic diagram of the machine is shown in Fig. 4. The storage ring consists of two semicircles almost spacelessly packed with bending and focusing magnets, separated by two long straight sections wherein the lenses provide the unity transfer matrices through the section for both lateral directions. The tune corresponding to the full circle is equal to $Q_{r,z} \approx 52$, correction facilities permitting the wide-range tuning.

The distributed magneto-discharge titanium pumps and radiation absorbers are mounted in the semicircles all around the orbit.

By now the behavior of the electron beam in the machine has been investigated; work is being carried on to obtain positrons in the amount great enough to start the experiment.

At the injection energy of 270 MeV we have succeeded in storing (harmonic number 1) electron current exceeding 200 mA using feedback to suppress the self-exciting phase oscillations of the bunch. Such a high current is not needed for the colliding beam experiments (at the first stage, in any case) but it is applied to the experiments with the extracted beam. The experiments of this kind, viz., the measurement of the $\Sigma^{\pm}$ hyperon magnetic moment by means of magnetic explosion generator (the magnetic field intensity available is about 1 MGS), are now under way. The electron bunch is used with the particle number as large as possible at the energy of 1.35 GeV.

The maximum use of the storage ring phase space is of great importance to store more positrons. To this end, injection is made with a great phase lag of the injected particles with respect to the equilibrium ones; RF harmonic number 1 is used. The injected bunch length is much less than the storage ring circumference; therefore, the next injection cycle can be repeated in a time much shorter than that of the radiation damping of the phase oscillations. This way of the storage procedure permits use of the entire lateral phase space of the storage ring without disturbance of the beam stored before. During the colliding beam operation the entire phase space (especially the vertical one) is not needed any longer but in return we want the lowest possible value for β-function in the collision point. In this connection the computer-controlled system of programmed timing of the supply currents of the lenses in the experimental straight section is developed. The particles stored in the entire phase space, the lens currents, were tuned so that the β-function in the collision point varies from 250 cm down to 38 cm without beam loss as the unity transfer matrices through the straight section persisted.

The energy has been brought up to 2.25 GeV only. The limit is set by the maximum RF voltage of 650 kV now available in the RF cavity with harmonic number 19 supplied with a 150-kW generator. Another cavity with harmonic number 45 supplied with the same power value is prepared at the moment which enables attaining the energy of 3 GeV.

In principle, storage ring VEPP-3 is convenient for obtaining polarized colliding beams. Since the average magnetic field is great as compared to those generally used for such an energy range, the polarization time at 3 GeV is equal to 2 minutes only. Preparation to obtain the polarized beams is under way now.

At present a channel for extraction of the synchrotron radiation is being made on VEPP-3. The radiation will be applied to X-ray diffraction structure analysis.

At the moment efforts are being taken that should enable us to store the positron currents high enough to start the experiments. But it is clear that the full-scale realization of VEPP-3 possibilities and especially of those of storage ring VEPP-4 (to be discussed later) requires a drastically greater value of the positron current. To this end an auxiliary "cooler" of positrong is now designed, which schematic view is shown in Fig. 5. Electrons of the maximum energy available from the synchrotron (about 400 MeV) are to be converted into positrons of an energy about 20 MeV and are to be injected into the "cooler." The cooler will capture the whole lateral emittance of the positrons (about 0.1 rad cm) within the energy spread of ± 10 percent. Then during one second the positron beam will contract due to radiation damping (the energy of positrong in the cooler will have to be brought up for a while to reach a greater damping rate). After that the thin positron beam will be transferred into the synchrotron, accelerated up to the maximum energy, and injected into the storage ring.

At present a new big storage ring is being constructed in our Institute. Anyhow, in our Institute's scale, it is an exceedingly big machine. In general, its arrangement is like that of VEPP-3. Figures 6 and 7 show the schematic view of the machine (not to scale), and the structure of the lattice magnet and of the vacuum chamber. In the first stage, the machine will serve as the electron-positron storage ring VEPP-4 at an energy up to 2×7 GeV.

The main regime envisages the injection of electrons and positrong from the storage ring VEPP-3 at an energy up to 1.8 GeV (use is made of the extracted beam experiment channel). However, during the stage of putting into operation and in order to operate the new machine in parallel with VEPP-3, injection directly from the synchrotron is also provided.

There are some peculiar features in the structure of the experimental straight section. An individual power supply for each lens enables the radical tuning of this straight section with the unity transfer matrices envisaged in particularly low β-function wherever needed. It is supposed to have three collision points (the free space between the lenses in these sections is of 7 meters). There is a magnetic field in the central section that bends the beam over 7 degrees (and in accordance with that, both semicircles bend the beam over the angle of $\pi - 3.5^o$). The aperture of this 7^o bending magnet is designed large enough (1.7 m $\times$ 2 m) to be used for momentum analysis of produced particles. The chosen configuration of the magnetic field is fitted to detect particles, particularly those produced in small angles.

By now the manufacturing of the storage ring magnets is completed and soon the manufacturing of the vacuum chamber will be over. The operation energy of VEPP-4 to begin with will be restricted to the value determined by the RF system available at that moment. The use of the RF system of VEPP-3 enables operation at 2×4.5 GeV. The availability of several sets of the kind may ensure the operation with currents 2×10 mA up to the maximum energy of 2×7 GeV.

The magnetic system of the machine is fitted to operate up to a momentum of 23 GeV/C. We plan to realize on it the proton-antiproton colliding beam experiments. However, an antiproton storage ring with electron cooling is necessary to this end. Now a small proton storage ring on 1/3 of the design value of antiproton momentum is assembled on the mounting of the future antiproton storage ring for the preliminary electron cooling experiments. The electron beam for the experiments has already been prepared and the setup is assembled in the straight section of the storage ring. Work on the proton injection is now under way.

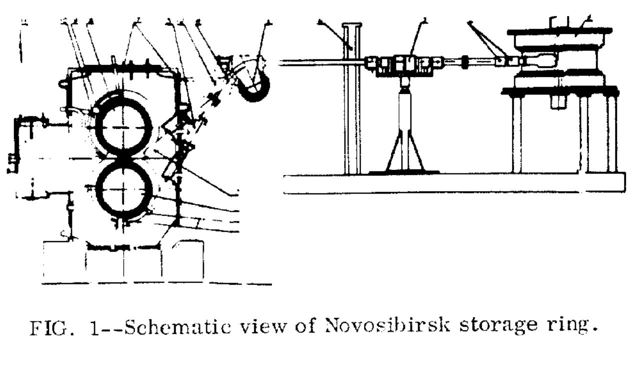

FIG. 1--Schematic view of Novosibirsk storage ring.

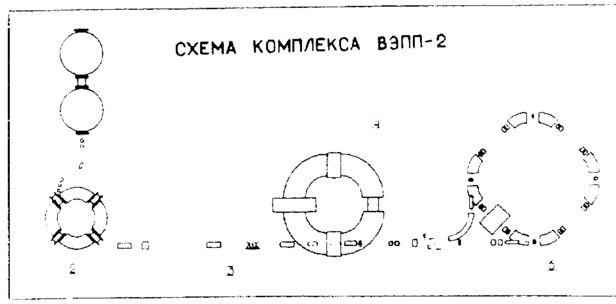

FIG. 2--Schematic of the VEPP-2 facility.

VEPP-2 experiments
(1967-1970)

$$e^+e^- \to \rho^o \to \pi^+\pi^-$$

$$e^+e^- \to \varphi \to \begin{cases} k^+k^- \\ k^o_S\, k^o_L \\ \pi^+\pi^-\pi^o \\ \pi^+\pi^- \\ \pi^o\gamma \\ \eta\gamma \end{cases}$$

$$e^+e^- \to \pi^+\pi^-$$
$$e^+e^- \to k^+k^-$$
$$e^+e^- \to n\pi$$
$$e^+e^- \to \mu^+\mu^-$$
$$e^+e^- \to \gamma\gamma$$
$$e^+e^- \to e^+e^- + e^+e^-$$

FIG. 3--Main experiments performed on VEPP-2 during 1967-1970.

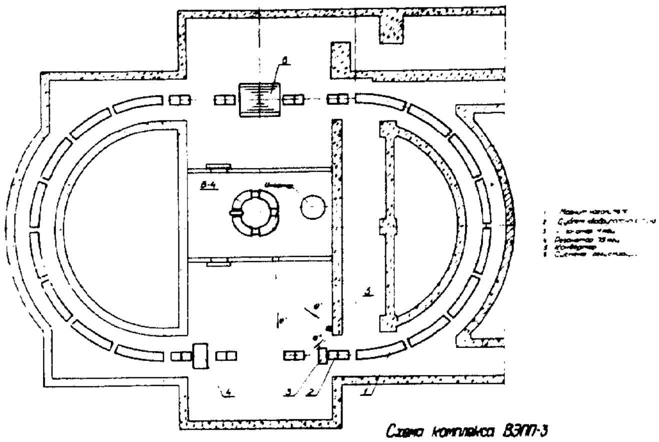

FIG. 4--Schematic of the VEPP-3 facility.

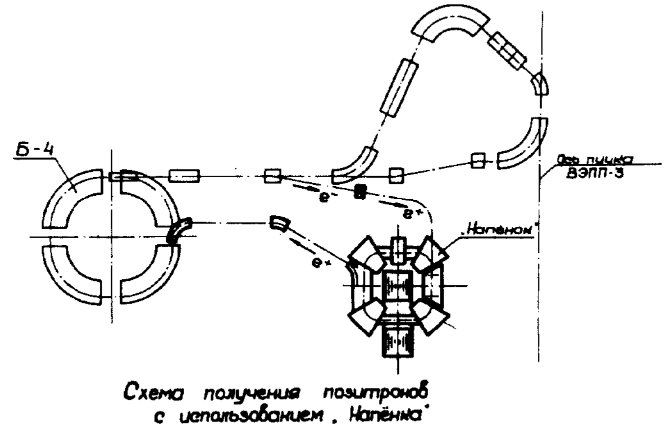

FIG. 5--Scheme for producing positrons using a "cooler".

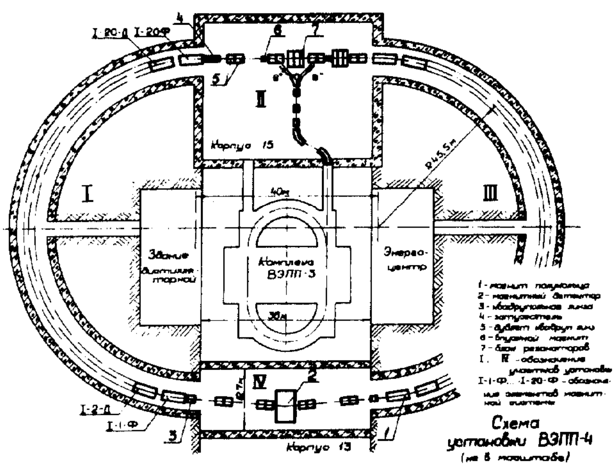

FIG. 6--Schematic of the VEPP-4 facility.

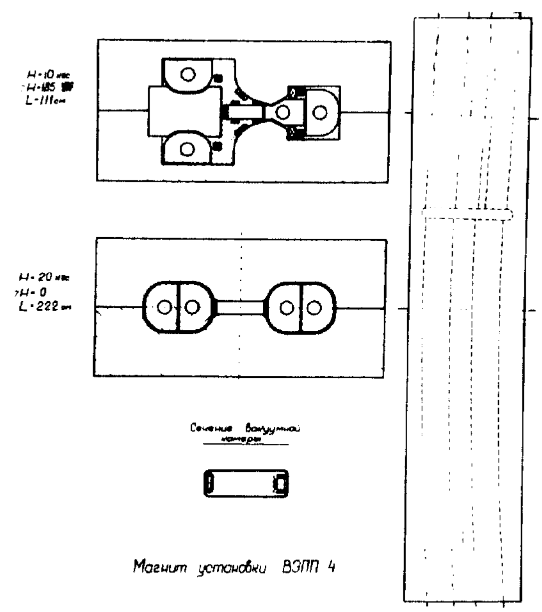

FIG. 7--Magnet arrangement at VEPP-4.