ACCELERATOR ACTIVITIES AT BUDKER INSTITUTE FOR NUCLEAR PHYSICS

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Abstract

Development of different kind of accelerator technologies is a base of the Novosibirsk Institute physical program. This talk gives a brief overview of a status and upgrade plans of the existing colliders VEPP-2M and VEPP-4 together with design and construction of the future Φ and Tau/Charm factories. Last achievements in the linear collider, free electron laser, electron cooling and polarized beams are presented.

1 COLLIDING BEAMS.

At the present moment two e^+e^--machines are in operation in our Institute.

1.1

VEPP-2M collider, which can be considered as the world first electron-positron pre-Factory, started to operate for experiments at 1975. The energy range of this machine is the lowest in the world $(150 - 700 MeV)$. But up to now, through all these long years, VEPP-2M remains with its luminosity $(5 \cdot 10^{30} cm^{-2} sec^{-1}$ on Φ-meson resonance) the main (practically the only) supplier of electron-positron physics results in this energy range [2], with several consequent steps in accelerator and detector upgrades, including construction of special more effective booster BEP. It is worth to pay special attention to the 8 Tesla superconducting wiggler magnet installed at VEPP-2M [3], which is in use for about 15 years to increase the radial emittance and the radiation decrements for luminosity enhancement and for suppression of intra-beam scattering.

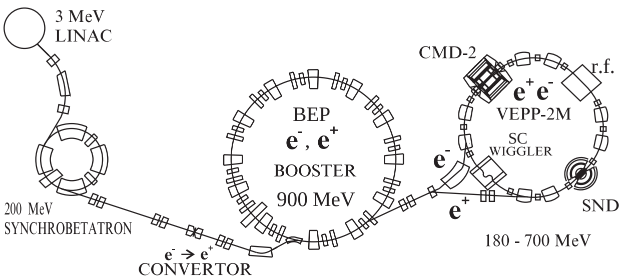

Figure 1: VEPP-2M scheme

The best intensity results reached up to now are $0.8 \cdot 10^{11}$ per bunch and $3 \cdot 10^{11}$ per bunch for VEPP-2M and BEP, respectively. The physics results obtained are reach. But it is worth to underline specifically the experiments, related to the achieving, study and use of polarized beams [4]. Currently, two new modern detectors, CMD-2 with super-conducting magnet spectrometer and SND with advanced crystal, high granularity, three layers electromagnetic calorimeter, carry out new set of front-line experiments. The main aims for the experiments are the very high precision measurement of hadron production in e^+e^- experiments (to be able to derive interesting physics from new muon $g-2$ experiment at BNL and to obtain as from Z-experiments at CERN) and study of rare, in many cases, still non-observed processes in light vector mesons sector.

1.2

Now in preparation is a new VEPP-2M upgrade - so called round beams option - as the way to rise additionally its luminosity [5, 6] and to prepare solid background for our Φ-Factory. The option implies several important issues:

a). Equal - and small! - beta values at Interaction Region $\beta_x = \beta_z = \beta_0$

b). Equal horizontal and vertical emittances, excited via quantum fluctuations independently up to the level, required for desired luminosity $\varepsilon_x = \varepsilon_z$

c). Equal betatron tunes $Q_x = Q_z$

d). Small positive (for e^+e^-) non-integer tune fraction $\{Q\}$

e). Low (tunable) synchrotron frequency Q_s

Items a), b) and c) lead to the conservation of angular momentum in transversal motion, thus converting this motion to one-dimensional one, with less beam-beam resonances, which can cause beam blow-up and/or degrade its lifetime. Items d) and e) proved in computer simulations to be useful in rising the maximal beam-beam tune shift $\xi_{\max}$, which does not damage luminosity. We hope to raise this value, at least, up to 0.1, in comparing with 0.05 - the best achieved up to now for flat beams. The additional useful effect arises due to the simple fact, that beam-beam tune shift for given counting bunch density is 2 times lower for round beams than for smaller dimension of flat beam.

Now we plan to implement the round beams option at the collider VEPP-2M.

The main change will be the replacing of quadrupole focusing at two interaction regions, equipped with modern running detectors, to solenoidal focusing (9 Tesla), that will give at the same time equal transverse emittances. This move will let us learn - just now - such non-traditional storage ring optics and study its tolerances, and reach real gain in $\xi_{\max}$ and in luminosity, rising it from current

$5 \cdot 10^{30} cm^{-2} sec^{-1}$ to $1 \cdot 10^{32} cm^{-2} sec^{-1}$. This improvement will give also a possibility to operate detectors at already very high fluxes of useful events.

1.3

Since 1980 the higher energy e^+e^- collider VEPP-4 is in operation at Novosibirsk [7]. Its maximal energy is $5.5 GeV$ per beam, and highest luminosity till now was $5 \cdot 10^{30} cm^{-2} sec^{-1}$. The main physics results are related to the Y family complementary studies, best full hadron cross-section measurements in the energy range, two-photon physics, and especially high precision mass measurements. Now, upon complete restoration after heavy miss-happening and upon major upgrade, the collider came in operation.

The main improvement is arranging of interaction region section as a double-arm high resolution, high efficiency spectrometer for electrons and positrons, which remain after reaction

$$e^+e^- \rightarrow e^+e^- + X$$

(the so called two-photon processes). It was proved experimentally, the X mass resolution reached in double-tagging is below $10 MeV$ for X masses $0.5 - 2.5 GeV/c^2$ with efficiency around 30% [8]. Such experiments would open, in particular, very important window in to the hadron spectroscopy in this mass region - complementary to the hadron beam and e^+e^- annihilation experiments. This approach would be of special importance for the separation of glueballs, four-quark states and "normal" two-quark states.

1.4

For number of years, the new generation of e^+e^- colliders - the super-high luminosity factories - are under development, in particular, at INP [9]. Now The VEPP-5 complex is under design and construction at Novosibirsk, which include the new injector facility to produce up to 10^{10} positrons and electrons per second with excellent emittances, the Φ-Factory and the Charm/tau Factory (the injector facility will feed the VEPP-4 collider, also).

1.4.1 Phi-Factory

The Novosibirsk Phi Factory project [6, 10] takes the full use of round beams approach and, additionally, combines both interaction regions at opposite azimuth in one, providing the very complicated and costly detector for CP violation studies with doubled luminosity. Each bending part of this storage device consists of two stores of dipole and quadrupole magnets; equal sign particles at the outer ends of solenoids are separated by magnetic field, while the opposite sign ones are separated electrostatically.

Such "Four-wing Butterfly" provides two options of operation. If number of equi-distant bunches of electrons and positrons is odd, the collisions occur alternatively (electron-positron, then positron-electron, etc..). Equal signs collision regions happens at a quarter of D_{bb} from IR, but the orbit separation is made magnetically, hence - much faster. The usual luminosity estimation (at $\beta_0 = 1cm$, bunch-bunch distance $D_{bb} = 400cm$) gives for this case

$$5 \times 10^{33} \mathrm{cm}^{-2} \mathrm{s}^{-1}$$

If number of bunches is made even, the collisions occur with uni-directional electron and positron bunches overlapping before each collision, thus providing compensation of coherent electric and magnetic fields. The beta-values at the collision point remain as small as in a previous mode, thus it opens possibility, with acceptable tolerances, to diminish emittances and/or to rise bunches intensity, thus reaching several times higher luminosity. (The e^+e^- luminosity is accompanied in this case by equal parasitic e^-e^- plus e^+e^+ luminosity.)

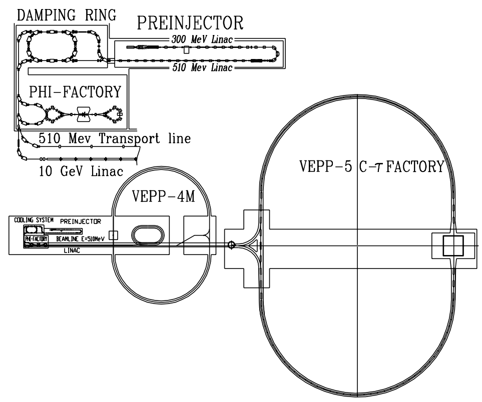

Figure 2: VEPP-5 complex layout

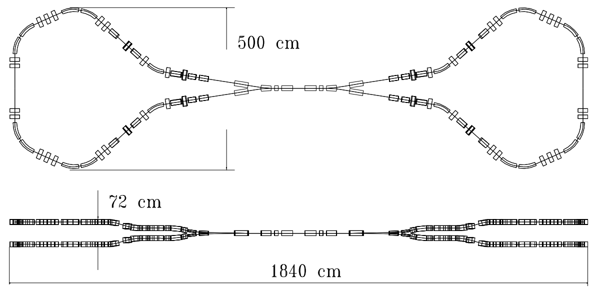

Figure 3: Φ-Factory scheme

1.4.2 C-τ Factory

The Charm/Tau Factory [11], which is a regular double ("two-stores") race-track storage ring with one Interaction Region, will be equipped with two, 2 meter long, 10 Tesla solenoids. At acceptably high beams emittances (a^2/β) about 1.5×10^{-5} cm (rms), excited in special wiggler sections installed at technical (opposite to IR) straight sections, the option gives at 2 GeV per beam luminosity

$$\times 10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-1}$$

For this project, two additional options are in preparation - with enhanced monochromaticity and with longitudinal polarization.

Usual electron-positron colliders provide already very good effective "mass-of-event" resolution - $\sqrt{2} \times \sigma_E \approx 5 \times 10^{-4}$. But there are resonances in annihilation channel, like Ψ and Y quarkonia, with much smaller energy widths, and it is of very interest to enhance substantially collider monochromaticity.

At the interaction region with very small (vertical) betatron size, energy dispersion is introduced, of opposite sign for electrons and positrons. Effective mass-of-event spread will be smaller than beam energy spread in proportion to the ratio of betatron size to "energy" size.

For our Charm/Tau factory, based on usual two-stores double ring with single IR, a flexible monochromatization option is foreseen. To excite energy dispersion at IR while keeping it zero at ring parts, in the long straight section on both sides of IR, independently for e^- and e^+, weak radial magnetic field is introduced, which changes its sign "in resonance" with vertical betatron oscillations. For additional vertical emittances suppression and for raising the beam energy spread, special wigglers are introduced in opposite to IR straight sections.

There is a hope to get

$$L = 1 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1} \quad \text{for} \quad \sigma_{Mass} = 40\mathrm{KeV},$$

and

$$L = 5 \times 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1} \quad \text{for} \quad \sigma_{Mass} = 5\mathrm{KeV},$$

Of course, all the problems with field stability etc. are assumed been solved. The final tracing of current energy is worth to arrange by the continuous bunch-by-bunch resonant depolarization.

This monochromatic option of Charm/tau Factory provides quite inspiring physics potential:

- to produce narrow Ψ resonances with much lower non-resonant admixture
- to complete charm-quarkonia spectroscopy;
- to measure directly with high precision the full width of charm quarkonia states;
- to produce, for example, 400 clean hc per second - via
$$e^+e^- \to \Psi \to \gamma\eta_c;$$
- to study τ-lepton pair production near threshold
- to measure τ mass with ultimate accuracy;
- to set τ-neutrino mass limit lower than 1 MeV;
- to study charmed barions threshold behavior;
- to ease substantially the study of possible $D\overline{D}$ mixing and CP violation (with adding a detector of a micron coordinate resolution);
- to measure masses with ultimate accuracy, using resonant depolarization;

2 LINEAR COLLIDER DEVELOPMENT

Since 1960s we did understand that the only way to hundreds of GeV electron-positron collider is to switch to linear single-pass colliders. We were able to present the self-consistent physics project of VLEPP linear collider at 1978 only, based on normal conducting pulsed linacs, when many important - basic - issues of the approach were specified and principal solutions found. Among the major issues were:

- transversal single bunch instability and its curing by along-the-bunch energy gradient (BNS damping);
- achievability of 100 MeV/m acceleration gradients;
- the beamstrahlung as basic - and flat beams to cure;
- beam-beam single pass instability limit;
- the possibility to produce short intense bunches of very low emittances - good enough for subsub-micron vertical size at final focus.

We did start the wide range R&D for this project, approved by the state authorities in principle. This project is stopped now because of dramatic changes in the country. But many important additional steps were made and are in progress now in linear collider physics, techniques and technologies - to be ready for the moment of Decision on World Linear Collider (when/if this happen).

- development of 14 GHz grided klystrons with 1 MV DC power supply and permanent magnets focusing structure - power of 50 MW at 90 dB amplification achieved at the prototypes;
- design and proof of effective peak power multiplication;
- design and prototyping of nanometer range beam position monitors and movers;
- the idea and algorithm development for adaptive linac positioning;
- effective cure of beam emittance stochastic blow-up by proper along-the-bunch energy distribution.

The concept of photon-photon and photon-electron option of linear collider was proposed and is now under development with INP active participation. Very slowly, but construction of 20 meter long test section is progressing at the Branch of our Institute at Protvino. If successful, VLEPP components will be used for post acceleration of electron and positron beams for VEPP-4 and Charm/Tau Factory injection. We also participate actively, from the very beginning, in Final Focus international experiments at SLAC and Test Facility here at KEK. The present status of the activity will be given in more details by V.Balakin in his talk on this conference [16].

3 ELECTRON COOLING

The synchrotron radiation cooling was crucial for the success of electron-electron and electron-positron colliders. It does not exist practically for heavier particles at modest energies. The first cooling method, applicable to protons and antiprotons, was proposed at INP by G.Budker at 1965 [13]. It was the electron cooling, when at some straight section of proton storage ring intense and "cold" electron beam of the same mean velocity accompanies the proton (antiproton) beam. In the common rest frame it looks as plasma relaxation with hot heavy particles and cold electrons, with relaxation time short enough for applications. In the next years the intense experimental and theoretical studies of the electron cooling were undertaken at INP [14]. The main results of these efforts are:

- the discovery, explanation and theory of super-fast and ultra-deep cooling;
- record results, reached at NAP-M cooler ring (1974-1979):
  - cooling time - 3 milliseconds,
  - longitudinal proton temperature - 1 Kelvin,
  - transversal proton temperature - 50 Kelvin;
- longitudinal ordering ("crystallization") of deeply cooled proton beam, and consequent suppression of intra-beam scattering.

Additionally, the special installation to study single-pass ("linear") electron cooling was built. The main results of these studies were:

- effective decrement reached was close to the theoretical limit $\Omega_{\rm eplasma} m_e/M_p$ – few meters of cooling length for 1 MeV protons;
- very substantial difference was discovered and explained for low temperature decrements of H^+ and H^- (for H^- and antiprotons everything is much better) - because of non-perturbative effects.

In parallel, intense search for areas of useful application of electron cooling was in progress at INP, and the great potential of coolers for elementary particle and nuclear physics was discovered and presented [15]. Now the electron cooling is in use at many laboratories throughout the world for antiproton and ion experiments, in some cases - with our active participation. The last electron cooler was produced at INP for GSI SIS heavy ion synchrortron at 1997. The energy of the cooled ions is limited today in the range 1-200 MeV/n. The new R&D programs is going on with the aim to use the 1-5 MeV electrons for the cooling at the antiproton accumulator (FNAL) [17] and at the ions collider at GSI [18]. It requires new systems for generation of the electron beams and a new level of the technical problems for the cooling stright section optics. The cooling of the intense ions creates additional troubles with coherent stabilities. The problems of the electron cooling will be presented on this conference in the special talk by V.Parkhomchuck.

4 POLARIZED BEAMS IN COLLIDERS AND ACCELERATORS

Polarized beams became one of the focuses in INP activity since mid-1960s. A greate numbers of theoretical considerations, inventions, practical applications and experiments with the polarized beams have been done on this long way. The more important of them are:

- the theory of the spin dynamics in the accelerators;
- the theory of the radiative e^+ and e^- polarization;
- the experimental study of the radiative polarization at our machines starting from VEPP-2 at 1970;
- the development of the different methods of the beam polarimetry;
- the beam energy calibration by the resonant depolarization and the seria of the precise measurements of the masses of $K^{+/-}$, K^0, ω, Ψ, Ψ', Y, Y', Y'' [4];
- the Siberian snakes and design of the spin rotators;
- the concept of the polarized e^+e^- linear colliders.

At last years we developed schemes of the longitudinal polarizations at VEPP-4 and at Tau/Charm factory. A real design of the rotator must be safe for the beam and minimized for beam polarization losses. These requirements have demanded a creation of new calculating methods for the spin and particle motion in the nontraditional complicate field configuration.

A special attention was paid to the rotator which rotates the spin by 180 degree on passage around longitudinal axis [19]. Such rotator which was called as Siberian snake creates the stable longitudinal polarization at the opposite point of the orbit and excludes in principle the depolarizing spin resonances because in this case the spin tune is always equal to 1/2. Two Siberian snakes have been build at INP for Amsterdam Pulse Stretcher ring and for MIT Bates laboratory [20]. In Amsterdam the polarized electron beam (120 mA) was stored with Siberian snake and 80 percents of the longitudinal beam polarization was measured on the energy 700 MeV by the laser polarimeter. A combination of two Siberian snakes (located at contra sides of the machine and with the rotation axises which are perpendicular to each other) provides also spin tune equal to 1/2 and the polarization along the guiding field in the arcs. This configuration is very stable against the radiative depolarizing effects for electrons, and opens the way for the polarized proton acceleration up to the high energy. A few pairs of the snakes make the TeV polarized protons available. Now programs with the high energy polarized protons are under development at BNL (RHIC) and DESY (HERA). A compact design of the snakes and spin rotators based on a helical superconducting magnets was suggested at INP (1994 [21]).

5 FREE ELECTRON LASERS

Synchrotron radiation sources for more than 20 years were in development and use at INP, including many novel and advanced storage ring conceptions and insertion devices, like superconducting wigglers (1978), permanent magnet undulators, fast switching electromagnetic undulators, etc.. Some of them are in operation at many dedicated SRS throughout the world. Status of SR facility will be cowered on this conference by prof. G. Kulipanov [22]

Some very brief words will be said about free electron laser developments, only. We are active in the field since the first demonstration of free electron lasing at Stanford, 1977. The first INP contribution was the invention of special FEL version - the Optical Klystron (1978, [23]), especially well suited for storage ring FEL operation. Successful operation of OK at VEPP-3 storage ring (1987, [24]). At this OK the lasing at 0.24 micron was achieved - the shortest among all the FELs up to now. Important achievement was also the very narrow band-width - up to $2 \cdot 10^{-6}$. Now we collaborate actively in the development and construction of dedicated storage ring at Duke University.

But the main goal in the field for INP now - the construction at Novosibirsk of high power laser for infrared to visible - up to 100 kW CW operation, based on dedicated microtron-recuperator [25]. Many novel concepts are incorporated in the project. More details about this project will be presented by N.Vinokurov [26]. The immediate application of this laser will be high scale photochemistry studies and technology developments. Among the more distant applications the most inspiring is to develop ground-based high efficiency and high scale power supply for future satellites, including geo-stationary ones.

6 HIGH POWER TECHNOLOGICAL ELECTRON ACCELERATORS

The development, design, construction and supply of high power, MeV energy range electron accelerators for technological applications [27] for decades is for INP a subject for care and an important source of additional investment in our basic research in high energy physics, fusion studies, etc. To the date, compact accelerators of two types - DC rectifier based and pulsed RF single-cavity based ones - are in serial production and more than 90 of them do operate successfully in technological lines of many countries, including more than 10 countries of "far abroad" (Japan, Germany, Poland, China, Korea, etc.). Its mean power ranges from 20 kW to 100 kW, and energy - from 0.7 MeV to 3 MeV. The wall-plug efficiency for 100 kW DC accelerator exceeds 85%.

Now we are ready to supply DC accelerators up to 0.5 MW mean power, and RF ones - up to 4 MeV, 30 kW.

7 CONCLUSION

Unfortunately, this brief view of the accelerator development at Novosibirsk INP is very incomplete. Even such important, well known and widely used INP concepts and devices, as charge exchange proton (ion) injection, high brightness negative ion sources, high field electron/ion optical elements like X-lenses and lithium lenses, girocon and magnicon high power pulsed and CW RF generators, single bunch injection/ejection systems applicable, were not even touched here. Of course, this development happened thanks to efforts and achievements of very many of our INP colleagues, most of whom could not be mentioned even in references. But we need to praise again A.M.Budker, who laid the background for the whole building.

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