ACCELERATOR ACTIVITIES AT BUDKER INSTITUTE OF NUCLEAR PHYSICS

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The talk presents briefly the current INP activity in the field of high energy accelerators for basic research and applications. More historical view was presented at PAC'95 /1/.

Accelerator field, especially for high energy physics, was always a core of the Institute activity, since its organisation in 1958. Under current difficult economic situation in Russia, with severe drop in State support for basic science especially, the Institute remains quite active both locally and internationally. The latter activity - participation in international and national projects abroad - gives us more financial support then all the internal sources combined. But in this talk I touch mostly our on-site activity.

ELECTRON-POSITRON COLLIDERS

The first collider experiments - the electron-electron ones - were performed in 1965 at Princeton-Stanford storage ring (Stanford) and at VEP-1 (Novosibirsk) /2/. The first (in the world) electron-positron experiments started in 1967 at VEPP-2 collider (Novosibirsk) /3/. At present, two e^+e^- colliders are in operation in our Institute.

The 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 $5*10^{30}cm^{-2}sec^{-1}$ on Φ-meson resonance the main (practically the only) supplier of electron-positron physics results in this energy range, 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 /4/, 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.

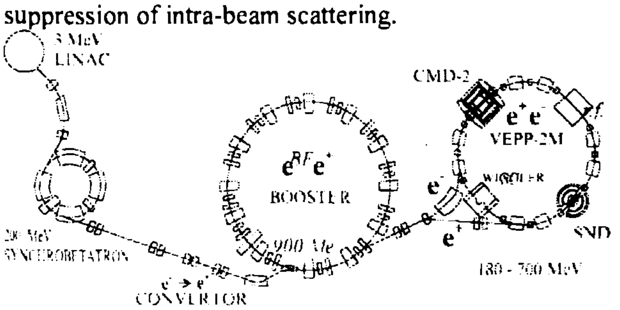

Figure 1. Collider complex VEPP-2M.

The best intensity results reached up to now are $0.8*10^{11}$ per bunch and $3*10^{11}$ 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 /5/. Currently, two new modern detectors: CMD-2 with super-conducting magnet spectrometer and SND with advanced high granularity, three layers crystal 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 running α_{em} from Z-experiments at LEP, CERN) and the study of rare, in many cases, previously non-observed processes in light mesons sector.

Now in preparation is a new VEPP-2M upgrade - so called round beams option - as the way to rise its luminosity /6,7/ and to prepare solid background for our Φ–Factory project. The option implies several important issues:

a) Equal - and small! - beta values at Interaction Region
$$\beta_x = \beta_z = \beta_0 = \sigma_{long};$$
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 fraction of tune Q;
e) Low (tuneable) 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 ξ_{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 ξ_{max} and in luminosity, rising it from current $5*10^{30}cm^{-2}sec^{-1}$ to $1*10^{32}cm^{-2}sec^{-1}$. This improvement will give also a possibility to operate detectors at already very high fluxes of useful events.

Since 1980 the higher energy e^+e^- collider VEPP-4 is in operation at Novosibirsk /8/. Its maximal energy is 5.5 GeV per beam, and highest luminosity till now was $5*10^{30}cm^{-2}sec^{-1}$. The main physics results are related to the Y family complementary studies, best full hadron cross-section measurements in the energy range 5-to-10 GeV (total), two-photon physics, and especially high precision mass measurements of Ψ and Y families.

Now, upon complete restoration after heavy miss-happening and upon major upgrade, the collider came in operation. The main improvement is the 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/c^2 for X masses of 0.5-2.5 GeV/c^2 with efficiency around 30% /9/. Such experiments would open, in particular, very important window in to the hadron spectroscopy in this mass region - complementary to the hadron beam and to the e^+e^- annihilation experiments. This approach would be of special importance for the separation of glueballs, four-quark states and "normal" two-quark states.

For number of years, the new generation of e^+e^- colliders - the super-high luminosity "factories" - are under development, in particular, at INP /10/. 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).

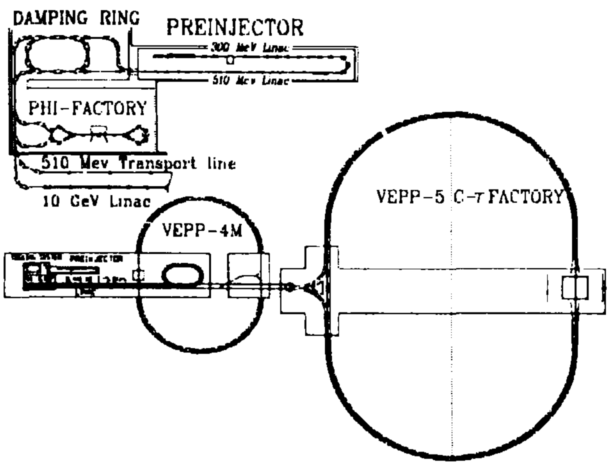

Figure 2: The collider complex VEPP-4 / VEPP-5 .

The Novosibirsk Φ-Factory project /7, 10, 11/ 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.

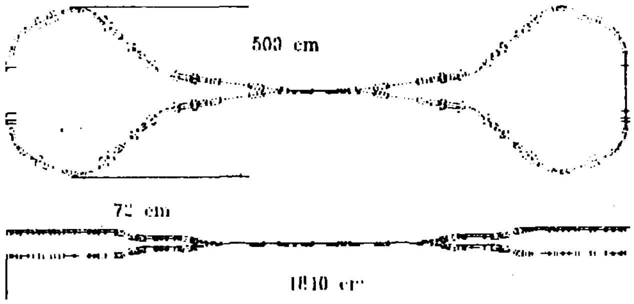

Figure 3: The Φ-Factory project.

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 the bunch-to-bunch distance D_{bb} from IR, but the orbit separation is made magnetically, hence - fast enough to prevent damaging beam-beam interaction. The usual luminosity estimation (at β_0=1 cm, D_{bb}=400 cm) gives for this case $5*10^{33}$ $cm^{-2}s^{-1}$.

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 additionally higher luminosity. (The e^+e^- luminosity is accompanied in this case by equal parasitic e^-e^- plus e^+e^+ luminosity.)

The prospect for this project depends on our success in round beams upgrade at VEPP-2M, on speed of DAPHNE project progress - and on the State financing.

The Charm/Tau Factory /10, 12/, which is a regular double ("two-stores") race-track storage ring with one Interaction Region, will be equipped - for "round beams" maximal luminosity operation - 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 $1*10^{34}$ $cm^{-2}s^{-1}$.

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 $2^{1/2}*\sigma_E \approx 5*10^{-4}$. 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, 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 to rise higher luminosity, special wigglers are introduced in opposite to IR straight sections.

There is a hope to get $1*10^{33}cm^{-2}s^{-1}$ for σ_{mass}=40 keV/c^2 and even $5*10^{33}cm^{-2}s^{-1}$ for σ_{mass}=5 keV/c^2 .

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 η_c per second - via $e^+e^- \rightarrow \Psi \rightarrow \gamma\ \eta_c$;

to study tau-lepton pair production near threshold;

to measure tau-lepton mass with ultimate accuracy;

to set tau-neutrino mass limit lower than 1 MeV;

to study charmed barions threshold behaviour;

to ease substantially the study of possible D-antiD mixing and CP violation (with adding a detector of a micron coordinate resolution);

to measure masses with ultimate accuracy, using resonant depolarization.

The Charm/Tau Factory option with longitudinally polarized electrons and positrons provides very interesting and important possibility to produce tau-leptons and charmed barions with extremely good degree of polarisation. The study of its weak decays should give much cleaner and precise knowledge for weak interaction in these sectors.

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 /13/. We were able to present the self-consistent physics project of VLEPP linear collider at 1978 /14, 15/, based on normal conducting pulsed linacs, when we have specified many important - basic - issues of the approach and have found principal solutions. Among the major issues were:

transversal single bunch instability and its curing by along-the-bunch energy gradient (BNS damping);

the beamstrahlung as basic - and flat beams to cure;

beam-beam single pass instability limit;

achievability of 100 MeV/m acceleration gradients;

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 at the Institute 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 (non-linear) 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 in Final Focus international experiments at SLAC from the very beginning and in klystron development at KEK. The present status of the activity will be given in more details by V.Balakin in his talk on this conference /16/.

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 for heavy particles, was proposed at INP by A.M.Budker at 1965 /17/. Just after this proposal we had realised, the electron cooling opens up very intriguing and important prospect for proton-antiproton colliders /18/, and this idea was for us the driving one to develop this completely novel accelerator technology, now so fruitful in the labs world-wide.

Electron cooling occurs when at some straight section of proton storage ring intense and "cold" electron beam of the same mean velocity accompanies the proton (ion, antiproton) beam. In the common rest frame it looks as plasma relaxation of 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 /19, 20, 21/. The main results of these efforts are:

the proof of principle and practical feasibility of the electron cooling;

the discovery, explanation and theory of super-fast and ultra-deep cooling;

record results, reached at NAP-M cooler ring (1974-1979):

cooling time (longitudinal) - 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 /22, 23/:

effective decrement reached was close to the theoretical limit $\Omega_{eplasma}m_e/M_p$ - 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 /24, 25/.

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 designed and constructed at INP for GSI SIS heavy ion synchrotron in 1997, and was put in operation successfully.

The energy of the cooled ions is limited today in the range 1-200 MeV/A. 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) and at the ions collider at GSI, the last collider conceptual project /26/, being presented at this Conference in the talk of K.Blasche. It requires new systems for generation of the electron beams and a new level of the technical problems for the cooling straight section optics.

For even higher ion energy we are developing now the new approach based on electron accelerator-recuperator concept /27/.

The cooling of the intense ions creates additional troubles with coherent stability.

The problems of the electron cooling will be presented on this conference in the special talk by V.Parkhomchuck.

POLARIZED BEAMS IN COLLIDERS AND ACCELERATORS

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

the theory of the spin dynamics, including careful study of spin resonances crossing in the accelerators and storage rings /28/;

the invention and theoretical proof of the ways to reach longitudinally polarised - at Interaction Region - beams at storage rings and colliders /29, 30, 31/;

the theory of the radiative e^+ and e^- polarization for complicated fields of real storage rings /32, 33/;

the invention and development of different methods of the beam polarimetry /34/;

the experimental study of the radiative polarization at our machines starting from VEPP-2 at 1970 /30/;

theoretical proof of possibility to reach reasonable degree of radiative polarisation at higher energies up to 100 GeV and even higher, when natural beam energy spread covers several external depolarizing resonances, and development of ways to raise the degree (1978) /35/;

invention of high precision beam energy calibration by the resonant depolarization and the series of the precise measurements of the masses of $K^{+/-}$, K^0, ω, ϕ, Ψ, Ψ', Υ, Υ', Υ'' /36, 37, 5/;

invention of Siberian snakes as the way to avoid spin resonances /38/;

development of different options of spin rotators;

development of different types of depolarizers;

the concept of the polarized e^+e^- linear colliders /39/.

Last years, we developed schemes for 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 non-traditional complicate field configuration.

Two Siberian snakes have been build recently at INP for Amsterdam Pulse Stretcher ring /40/ and for

MIT Bates laboratory. 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 axes which are perpendicular to each other) provides also spin tune equal to ½ and the polarization along the guiding field in the arcs. This configuration is very stable against the radiative depolarizing effects for electrons, and for the polarized protons opens the way for acceleration up to the high energy without loss of polarization. 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) with some INP involvement. A compact design of the snakes and spin rotators based on a helical superconducting magnets was proposed and developed at INP (1994) /41/.

MUON COLLIDER

We started to search ways for muon-muon collisions still in 60s. Our initial considerations were presented at Morges Seminar, 1970 /13/ and at XX High Energy Physics Conference at Madison, 1980 /15/. More complete consideration of ionization cooling, its application to produce intense and low emittance muon beams, evaluation of muon collider luminosity and its conceptual description was presented 1982 /42/.

But only since 1990 the field attracted world-wide interest. Currently, INP participates the international Muon Collider Collaboration.

The main R&D activity of INP focuses in following directions, which we consider as crucially important for future scientific productivity of the field /43, 44, 45/:

final cooling - with the aim to reach ultimately small 6-emittance, including development of liquid lithium high current long rods with surface field above 10 Tesla;

liquid (heavy) metal target (esp. pulsed);

multi-channel system for pion collection/ pion-to-muon decay - to produce highly polarized muon bunches.

lithium jet suppression of muon beam-beam disruption (becomes useful for very cold and intense muon bunches).

EXTREME ACCELERATION

Since 1960s - 1970s, INP investigated options for reaching 100 MeV/meter accelerating gradients:

super-linacs - "conventional" klystrons/girocons driven sectional linacs - the core part of linear collider projects (VLEPP for INP /14, 15/);

linear structures driven by along the axis traveling properly bunched proton beams of high energy accelerators (huge stored energy available!) - "proton klystron", 1977 /46, 47, 48, 15/. Now such options are called "Two Beam Accelerators".

Nowadays, such gradient is "normally high accelerating gradient", reached in several labs in test installations and is incorporated in linear collider projects.

For accelerating gradient 1 GeV/meter (and somewhat higher), "under attack" in many labs, INP focuses (very modest) efforts on the concept of Beam Driven Plasma Wake Field Acceleration (not Laser Driven!) - as possible backbone for very high energy (polarized) electron, positron, kaon acceleration and for photon-photon / photon-electron colliders.

The main physics results and conceptual INP findings in the field are /49, 50, 51/:

the most efficient and stable way for driver beam excitation of high accelerating gradients is the train of high energy microbunches of lengths and radii equal to c/ω_{pl};

all the driver beam and the beam under accelleration particles shall travel in focusing phases of plasma oscillations;

the microbunches should be prepared with inverse FEL pre-bunching and transversal RF final cutter;

sequential acceleration with final energy 100 higher than driver beam energy is feasible;

final focus can give very low IR beta-value of < 1mm is feasible with the use of beam driven plasma focusing;

multiple scattering in plasma channel under extremely strong plasma focusing gives small enough final emittance to reach quite good photon-photon and electron-photon (but not for $e^{+/-}e^{-}$!) luminosity in collider mode (at acceptable level of power consumption).

SYNCHROTRON RADIATION SOURCES AND FREE ELECTRON LASERS

Synchrotron radiation sources for 25 years are in development and use at INP /52, 53/, including many novel and advanced storage ring /54/ and light source concepts /55, 56/ and insertion devices, like superconducting wigglers (1978), permanent magnet undulators, fast switching electromagnetic helical undulators, etc.. Some of them are in operation at many dedicated SRS throughout the world. Status of the SR activity, as well as of the FEL one, will be covered on this conference by N.Vinokurov.

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) /57/, especially well suited for storage ring FEL operation. Successful operation of OK was achieved at VEPP-3 storage ring (1987) /58/. At this OK the lasing at 0.24 micron was reached (1989) - the shortest among all the FELs up to last months. Important achievement was also the very narrow band-width achieved - up to $2*10^{-6}$. Now we collaborate actively in the development and construction of dedicated storage ring and OK 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 /27/.

Many novel concepts are incorporated in the project. More details about this project will be presented by N.Vinokurov /59/.

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.

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, 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 I want to praise again A.M.Budker, who laid the background for the whole building.

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