ACCELERATOR FIELD DEVELOPMENT AT NOVOSIBIRSK (HISTORY, STATUS, PROSPECTS)

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Abstract

In this talk an attempt is made to present INP contribution to the accelerator field in inventions, discoveries, theoretical and experimental studies of related phenomena, in design, construction and application of accelerator complexes. There are presented only events and aspects where the Institute was a pioneer or achieved the ultimate results to the moment of their publication.

Our team was arranged initially as the Laboratory of New Acceleration Methods, of the Institute of Atomic Energy (Moscow), under leadership of Prof. G. Budker. Then, at 1958 the Laboratory was transformed in to the Institute of Nuclear Physics and we moved to Novosibirsk. Through many years, till his passing away in 1977, Prof. G. Budker remained the director of our Institute, which is now named after him.

I. COLLIDING BEAMS

The INP high energy physics prospects and experiments are based, from the very beginning, on colliding beams, mainly. This activity started just upon D. Kerst's proton collider suggestion and G. O'Neil's proposal to use radiation damping for electron beams storing and compression. And the first years our efforts (since 1957) were focused on physics development, design and construction of electron-electron collider VEP-1.

Many laboratories throughout the world became active in the direction, and, upon the first beams storing at AdA (Frascati), two of them, Stanford-Princeton group and Novosibirsk group, were the first in reaching the real HEP experiments stage. These two groups carried out electron-electron scattering experiments in 1965-1967.

1.1. At VEP-1 collider, the maximum energy was 2×0.16 GeV, and maximum luminosity 3×10^{27} cm^{-2} sec^{-1}, and elastic scattering and double bremsstrahlung experiments were performed [1].

The main achievement of these Princeton-Stanford and Novosibirsk experiments was the proof of real possibility to perform colliding beams experiments for elementary particle physics.

1.2. The world first electron-positron experiments were performed at Novosibirsk collider VEPP-2 at 1967: the ρ-meson parameters were measured via electron-positron annihilation in to two pions [2]. Afterwards, many electron-positron colliders were and are in operation, starting, still in 1960s, of ACO (Orsay) and CEA (Cambridge), bringing a lot of very important results and discoveries.

The VEPP-2 collider was in operation for electron-positron experiments 1967 - 1970, providing energy up to 2×0.7 GeV and luminosity up to 2×10^{28} cm^{-2}sec^{-1}. The main results are related to ρ-, ω-, ϕ-mesons parameters and decay modes studies, discovery of multi-hadron production above main vector mesons region and first observation of two-photon e^+e^- pair production, which was the world start of two photon physics [3].

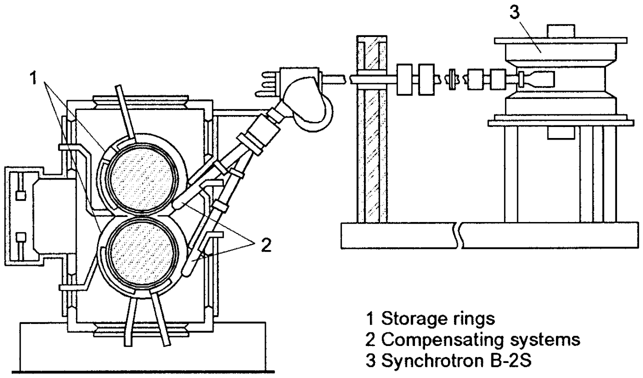

Figure 1. Layout of the VEP-1 Installation

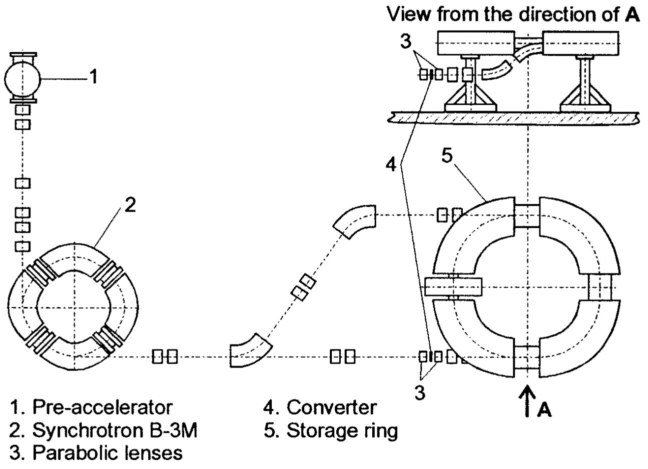

Figure 2. Layout of the VEPP-2 Installation

1.3. The next Novosibirsk e^+e^- collider VEPP-2M, which can be considered as the world first electron-positron "pre-Factory", started to operate for experiments at 1975 [4]. The energy range was just the same as of VEPP-2, but the luminosity reached was more than 100 times higher: up to 5×10^{30} cm^{-2} sec^{-1}. The initial VEPP-2 storage ring served for a long time as VEPP-2M booster. Up to now, through all these long years, VEPP-2M remains the main (practically the only) supplier of electron-positron physics results in its energy range [5], with several consequent steps in accelerator and detector upgrades, including construction of special more effective booster BEP.

It is worthwhile to pay special attention to the 8 Tesla superconducting wiggler magnet installed at (such a low energy storage ring!) VEPP-2M, [6] which is in use for about 15 years to increase the radial emittance and the radiation

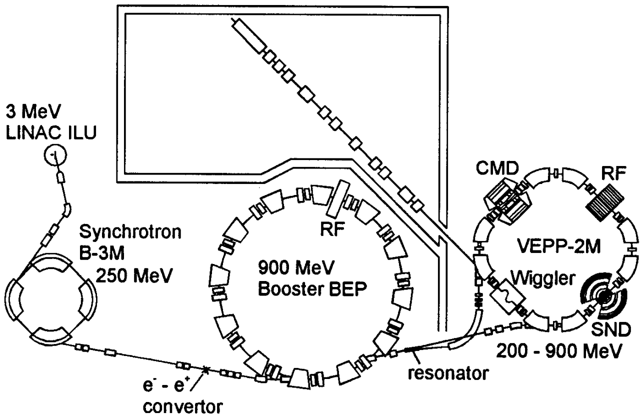

Figure 3: Layout of VEPP-2M Complex

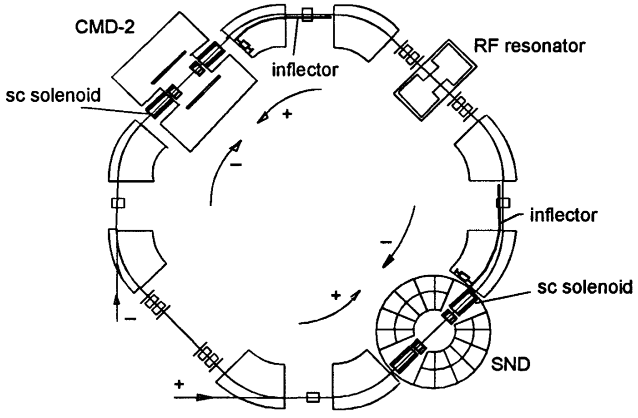

Figure 4: Layout of the VEPP-2M storage ring.

decrements for luminosity enhancement and for suppression of intra-beam scattering.

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 rich. But it is worth to underline specifically the experiments, related to the achieving, study and use of polarized beams [7] (Ch. 5).

Currently, two new modern detectors, CMD-2 with superconducting 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 α_s from Z-experiments at CERN) and study of rare, in many cases, still non-observed in processes light vector mesons sector.

1.4. Now in preparation is a new VEPP-2M upgrade (so-called "round beams" option) as the way to rise additionally its luminosity [8,9] and to prepare solid background for our Phi Factory.

The option implies several important issues:

a) Equal - small! - beta values at Interaction Region $\beta_x = \beta_z = \beta_0$;
b) Equal horizontal and vertical emittances, excited via quantum fluctuations <u>independently</u> up to the level, required for desired luminosity $\varepsilon_x = \varepsilon_z$;
c) Equal betatron tunes with "zero" coupling ("no" tunes splitting) $Q_x = Q_z$;
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 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 two 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 $5\times10^{30}\text{cm}^{-2}\text{s}^{-1}$ to $1\times10^{32}\text{cm}^{-2}\text{s}^{-1}$. This improvement will give also a possibility to operate detectors at already very high fluxes of useful events.

1.5. Since 1980 the higher energy e^+e^- collider VEPP-4 is in operation at Novosibirsk [10]. Its maximal energy is 5.5 GeV per beam, and highest luminosity till now was 5×10^{30} $\text{cm}^{-2}\text{s}^{-1}$. The main physics results [11,7] 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 (Ch. 5).

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 $e^+ e^- \to e^+ e^- + X$ (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%. 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.

1.6. For number of years, the new generation of e^+e^- colliders (the super-high luminosity factories) are under development, in particular, at INP [12]. Now The VEPP-5 complex is under design and construction at Novosibirsk,

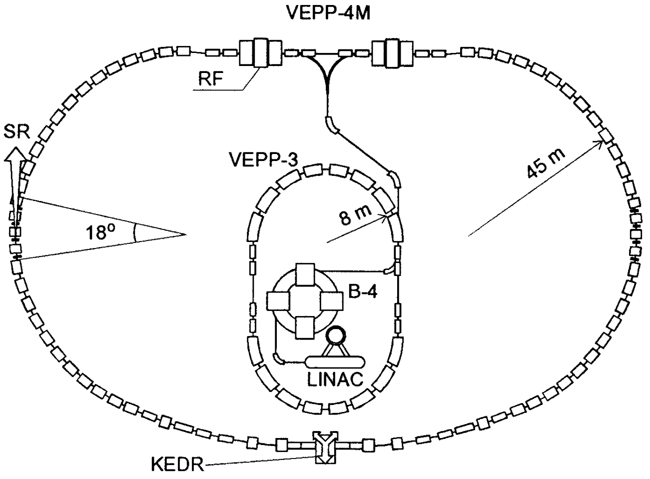

Figure 5: VEPP-4M

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).

1.6.1. The Novosibirsk Phi Factory project [13,9] 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.

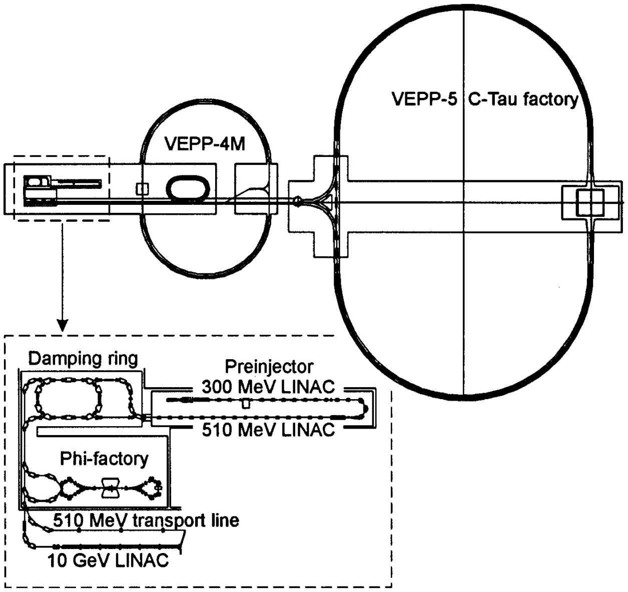

Figure 6: General Layout of the VEPP-5 complex

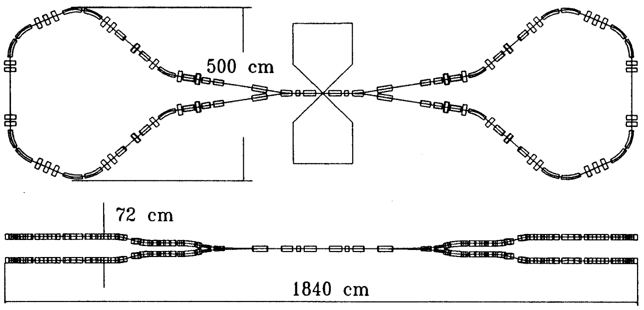

Figure 7: Layout of the Novosibirsk Phi Factory.

The usual luminosity estimation (at β_0=1 cm, bunch-bunch distance 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 higher luminosity. (The e^+e^- luminosity is accompanied in this case by equal parasitic e^-e^- plus e^+e^+ luminosity.)

1.6.2. The Charm/Tau Factory [14], 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 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: $\sqrt{2}\sigma_E \approx 5\times10^{-4}$. But there are resonances in annihilation channel, like Ψ and Υ quarkonia, with much smaller energy widths, and it is of very interest to enhance substantially collider monochromaticity. This idea appeared at Novosibirsk immediately upon J/Ψ particle discovery, and different options were studied.

The general idea is quite simple and straightforward. 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 ē 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 = 1×10^{33} $cm^{-2}s^{-1}$ for $\sigma_{Mass} = 40$ keV and L = 5×10^{31} $cm^{-2}s^{-1}$ for $\sigma_{Mass} = 5$ 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 – for the study of rare and difficult-to-separate decays;

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 $e^+ e^- \to \Psi \to \gamma\, \eta_c$;

to study τ-lepton pair production near threshold, 0.5 pairs/sec at threshold, 3000 $\tau\tau$ atom/day – possibly sensitive to the New Physics;

to measure τ mass with ultimate accuracy;

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

to study charmed baryons threshold behavior;

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

to measure masses with ultimate accuracy, using resonant depolarization; etc

II. LINEAR COLLIDER DEVELOPMENT

Since 1960's we did understand that the only way to hundreds of GeV electron-positron collider is to switch to linear single-pass colliders. And at International Seminar on High Energy Physics Prospects (Morges, 1971) these considerations were presented [15]. We considered there two options: the use of superconducting linacs with energy recuperation, and the normal conducting pulsed linacs approach. As more promising we scored the superconducting option.

But 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 [16,17]. Among the major issues were:

single bunch high efficiency energy extraction;

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 happens).

Especially important steps made are:

development of 15 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 [18].

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.

III. 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, was proposed at INP by G. Budker at 1965 [19]. It was the electron cooling, when at some straight section of proton storage ring intense a "cold" electron beam of the same mean velocity accompanies the proton beam. In the common rest frame it looks as plasma relaxation with hot protons and cold electrons, with relaxation time short enough for applications. The initial aim of the proposal was storing of high proton currents for proton-proton collider. But immediately upon the invention, again at INP, it was proposed to use electron cooling for storing of antiprotons to arrange proton-antiproton collisions of high luminosity. The dedicated proton-antiproton complex for 46 GeV (total) was designed and, partly, constructed [20]. But upon construction of the FNAL Main Ring, which could carry out antiproton experiments of comparable energy as stationary target ones, we gave up this intention and converted project in to electron-positron collider VEPP-4.

The idea of electron cooling was met by the world community with interest, but for the next 9 years nobody tried to develop and to apply the idea. During these years the physics of electron cooling was studied at INP theoretically [21], a dedicated proton storage ring NAP-M (Russian abbreviation for "Storage ring for AntiProtons - a Model") was designed and built, and a special device to produce electron beam of perfect parameters was developed, constructed and installed at NAP-M.

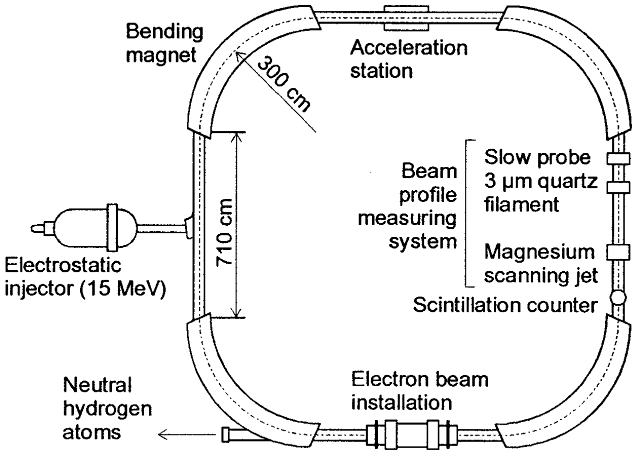

Figure 8. Layout of the proton cooler ring NAP–M

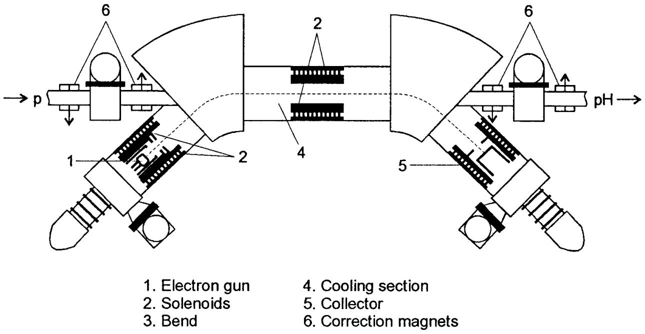

Figure 9. Layout of the electron-beam device for electron cooling.

The world situation changed dramatically at 1974, after first successful experimental demonstration of the electron cooling [22].

In the next years the intense experimental and theoretical studies of the electron cooling were undertaken at INP [23,24]. The main results of these efforts are:

the discovery, explanation and theory of super-fast and ultra-deep cooling - because of very low longitudinal electron temperature and "magnetization" of electron transversal velocities; as a result, 100 times faster cooling, then our initial hopes;

record results, reached at NAP-M (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 [25]:

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 [26,24].

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.

IV. IONIZATION COOLING AND MUON COLLIDERS

The ionization cooling was for a long time under consideration in different laboratories. We at INP got interested in this method since the end of 1960s, having in mind muon-muon colliders [27]. For us it was clear, that the muons are the only particles, for which ionization cooling might be of crucial importance: for them, there are no nuclear interactions and no bremsstrahlung at the parameters of interest.

We presented the ionization cooling as the way to reach high luminosity at hundreds of GeV muon-muon collider at 1971, at the same Morges Seminar [15]. The scheme presented did include the steps:

to obtain a very large number of protons with tens of GeV energy in rather short bunches;

to produce with maximum efficiency muons with 1 GeV energy, using nuclear cascade for pion production, strong focusing at conversion target and at pion decay channel;

to cool muons in special hundred kilogauss pulsed storage ring, using ionization energy losses. If the targets are at azimuths with very small beta-functions, the final emittance of muon beam shell be small enough to be injected into the main muon accelerator with small aperture and to be well compressed in interaction points;

to accelerate muons rapidly in some accelerator; if the muon energy is increasing several times of $m_\mu c^2$ during their rest frame time τ_0, most of the muons will be accelerated up to final energy. It is possible to use a linear accelerator, or to use a fast pulsed synchrotron;

to arrange collisions at storage ring (or cyclic accelerator) with 100 kGs guide field (In the case of pulsed ring, the collider can serve at the same time as main accelerator.) In such ring it is possible to have several thousand of useful turns before muon decay.

Then we considered the most important aspects and details of ionization cooling in 1980 and 1981 [24]. But only quite recently muon colliders and ionization cooling attracted the interest of several groups. The next step should be the development of practical test facility and experimental proof of possibility to reach really high efficiency of transforming of protons in muon beam of low emittance (corresponding to the ionization cooling limits); the facility should include an advanced proton-to-pions conversion system.

The immediate goal for this efforts could be to supply high intensity, low emittance muon beam for ultra-high precision muon g-2 experiment at BNL.

V. POLARIZED BEAMS IN COLLIDERS AND ACCELERATORS

Polarized beams became one of the focuses in INP activity since mid-1960s, initially in theoretical considerations and inventions, and in a few years, in experiments and applications.

5.1. Just upon theoretical discovery of synchrotron radiation polarization mechanism for electrons (positrons) in homogenous magnetic field [28], intense studies of the process in “practical” accelerator fields started at INP. It was proved, the process does exist in this case [29], but does appear a specific mechanism of depolarization due to “machine” spin resonances, under influence of energy jumps caused by quantum fluctuation of radiation in presence of vertical orbit perturbation [30]. Then the practical method of calculation of polarization time and equilibrium polarization degree in arbitrary complex fields was developed [31], based on the discovery of existence of closed spin orbit $\vec{n}(\theta)$ for any closed “coordinate” orbit [32], followed by design of corresponding perturbation theory [33]. It was shown, that depolarization rate is higher if the dependence of $\vec{n}$ on energy for the storage ring under consideration is higher. Afterwards, a very effective method of depolarization suppression was proposed and designed (section 5.7).

A special attention was paid to the very high energy storage rings, because of suspicions in HEP community appeared on complete deterioration of polarization if the beam energy spread becomes (much) larger then energy separation (440 MeV for electrons) of main machine depolarizing resonances, what happens around 30 GeV. It was shown [34], that by proper correction of spin-resonansing harmonics of the storage ring radial magnetic field it is possible to reach good polarization degree even (then future) LEP ring. Especially effective approach could be the following: to install at few azimuths of (long) storage ring with “very” low magnetic field the high field asymmetric wigglers and local spin-chromaticity correctors.

Electron beam radiatively polarized for the first time was reached at our storage ring VEPP-2 and at ACO at 1970 [35]. In this experiment external RF resonant depolarization was used for the first time, afterwards proved to be such an efficient tool in applications (section 5.3). The process of radiative polarization, the depolarizing factors and their curing were studied in details at other INP storage rings [36].

5.2. An important part in all the polarization dealings is development of polarization degree and (local) polarization direction measurement methods at storage rings without beam loss, especially for electrons and positrons. Most of them were proposed at INP, but are in use everywhere:

spin-dependence of energy exchange due to intra-beam scattering [37];

effective for low energies - up to 2-3 GeV - used at VEPP-2, ACO, VEPP-3, SPEAR, BESSY;

up-down asymmetry in backward scattering of circularly polarized laser photons [37] effective for higher energy range 2 to 100 GeV - used at SPEAR, DORIS, CESR, VEPP-4, PETRA, PEP, TRISTAN, LEP;

same asymmetry in helical undulator photons scattering - used at VEPP-2M [38];

same asymmetry in synchrotron radiation photons scattering (upper vs. lower parts) [39]; specifically effective for simultaneous measurements for both colliding beams - used at VEPP-4;

spin-dependent fraction of synchrotron radiation [40]; effective for high energies and high (local) magnetic field - successfully tested at VEPP-4 [40];

may be of specific interest for continuous (or instant) measurements at very high energy storage rings with the use of specific e^+e^- pair detector [41].

5.3. Implementation of RF induced resonant beam depolarization, started at VEPP-2 experiments, 1970, was an important step in the field. It gave possibility to depolarize electrons and positrons without any changes in their orbital motion (for example, without machine resonance crossing by energy change), what is helping a lot, at all labs, in beam polarization studies.

But the most productive application is the very high precision measurement (up to 1×10^{-6}) of mean beam energy at colliders [4] by scanning measurement of spin precession frequency of electrons and positrons. This method gave us possibility to measure at VEPP-2M and at VEPP-4 the masses of $K^{+/-}$, K^0, ω, Ψ, Ψ’, Υ, Υ’, Υ’’ [7]. The accuracy of Υ meson reached at 1985 was 1×10^{-5}, and still remains the world best in the area.

The method was successfully applied at CESR, DORIS and LEP colliders.

Upon solving difficult and tricky technical problems (field stability, higher statistics, etc.), it would be possible to enhance additionally (up to 2 orders) the accuracy of mass measurements.

The same approach was used for precise comparison of e^+ and e^- magnetic moments. But even better results were obtained with the use of RF simultaneously induced spin resonance without depolarization. If to switch off the amplitude of spin-precession exciter just at the moment of resonance crossing, the spins of both beams particles will precess in horizontal plane coherently for many cycles. If to restore the RF amplitude at the resonant frequency and scan frequency back, the final direction and degree of polarization depend on relative phase of electrons and positrons precession. This approach gave possibility to prove equality of electron and positron magnetic moments at VEPP-2M collider with the accuracy 1×10^{-11} [42].

5.4. RF depolarizers and flippers. Physical measurements of spin dependent phenomena demand very often a fast polarization reverse or full depolarization of the beams while orbital beam parameters are not changed. To achieve these goals, special RF devices were suggested and developed (1970,1980). To reverse the polarization of the stored beam, the frequency of an RF electromagnetic field is swept adiabatically across a resonance with the spin precession frequency. An amplitude of the RF field and its configuration requirements depend on a direction of polarization, the beam energy and conditions of experiments.

For electrons, in the simplest case of the transverse polarization a RF solenoid provides the adiabatic rotation of the polarization in the energy region up to few GeV. On higher energy the use of electromagnetic field which is transverse to the beam trajectory is more effective, because in this case the spin rotation angle is proportional to spin tune

$$\nu_s = \gamma \cdot \frac{\mu_{an}}{\mu_0} >> 1.$$

Under such consideration the RF-power about 1-3 kW is enough for the robust polarization reverse at any existing storage ring.

The same RF-devices on a low power can give the fast beam depolarization due to a natural or external noise when the frequency of the excited field coincides with the spin precession frequency [33].

With a proper choice of the depolarizer's parameters a synchronous detecting of the beam depolarization indicates the spin tune with an accuracy of the spin tune spread

$$\delta\nu_s \approx 10^{-5} \div 10^{-6} \quad .$$

5.5. Since longitudinal beam polarization is more interesting for physical experiments, special spin rotators are used to bring polarization along particle momentum in the Interaction Point. A number of the spin rotators with different field combinations were proposed in the middle of the 70's. 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 any axis [43]. Such rotator 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.

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; 44].

5.6. A step in polarization related development at storage rings, which we consider as very important and even crucial, was made in 1969, when the way to reach longitudinally polarized colliding beams was discovered and proved theoretically [32]. Opposite to the common sense of that time that only transversal to the orbit plane spin direction can repeat at every turn continuously, it was shown that for any closed orbit $\vec{r}(\theta)$ the corresponding closed spin "orbit" $\vec{n}(\theta)$ does exist, which is as stable out of spin resonances as in the usual purely transversal case. Hence, by adding of some combination of longitudinal and transversal magnetic fields along the storage ring orbit (so called spin rotators of different kind) it is possible to arrange any stable spin direction at a given azimuth. In particular, longitudinal polarization in interaction region of a collider can obtained, and for both beams in a time.

The simplest spin rotators use some distribution of radial magnetic fields, which bend the beam orbit in vertical direction. In this case, if at the electron-positron interaction region the vertical inclination of the orbit is

$$\frac{\pi}{2} \cdot \frac{1}{\gamma} \cdot \frac{\mu_0}{\mu_{an}} = \frac{\pi}{2} \cdot \frac{440}{E_{MeV}},$$

colliding beams are longitudinally polarized.

Of course, the practical spin rotation layout is strongly dependent on the beam energy and specificity of the storage ring [45,14].

Quite recently, very good degree of longitudinal polarization was achieved at HERA electron ring.

5.7. Just upon the first presentation of INP linear collider approach it was understood, that the use of helical undulator radiation of spared electrons and positrons, is possible to reach polarized e^+e^- collisions [46,17]. The longitudinally polarized photons of several MeV hit the targets, the upper half of $e^+(e^-)$ is collected and at the end of 1 GeV pre-accelerator we get longitudinally polarized $e^+(e^-)$ with high degree of polarization and reasonable monochromaticity. After passing spin rotators vertically polarized $e^+(e^-)$ are injected in to cooler rings. Upon reaching final normalized emittance and passing proper spin rotators, the particles enter their main linacs and collide at the detector with arbitrary chosen helicities.

5.8. The possibility to arrange (at a given azimuth of a storage ring) stable longitudinal polarization, opens the way to polarize, say, stored antiprotons, using difference in cross-section for different helicities - the so called spin filtering [26,47]. To achieve the aim, it is worth to use gas (gas-jet) proton target, polarized in the direction of antiproton velocity.

The best layout is to use super-thin target regime (Ch. 7) with electron cooling.

Quite recently, this approach was successfully tested for protons at GSI (Darmstadt).

VI. EXTREME ACCELERATION GRADIENTS

In the process of our search of the ways for linear colliders, it was understood and proved experimentally, that acceleration gradients at the level of 100 MeV/m can be achieved at properly designed normal conducting accelerating structures in short pulse mode (Ch. 2).

One of the ways to power such linacs is to use stored energy of extremely high energy proton beams - the so called "proton klystron" approach [48,17].

To achieve much higher accelerating gradientsÑup to 1 GeV/m - it is almost inevitable to use plasma based devices. For decades, this direction was studied theoretically and experimentally in many labs, and several approaches were studied. Among them: smokotron, laser beam excitation, two laser beams beat-wave acceleration, plasma wake field acceleration (PWFA).

The last one - PWFA - up to now was based, in considerations and experiments, on driver electron beams of modest energy - the most natural transition from electron beams of klystrons, which excite usual linacs. But, in our understanding, it is not the way to extreme gradients: we need to use as high energy - "rigid" - beams as economically possible, with high linear density and low emittance. This is the way to overcome plasma and beam-plasma (local) instabilities and toreplace efficiently the accuracy of solid surfaces, which shape fields in usual linacs [49,50]. And a very important component of the whole approach is to arrange a proper focusing channel to keep the beams "very carefully" aligned.

One of the key elements of the approach is to find the way to introduce proper micro-bunching in to the driver beam - at about 1 mm wave length.

The way proposed to solve this problem is to use very low emittance beams and transversal cutting. The general layout looks as following. At some part of the beam channel with high beta value, say, in vertical direction, we arrange local RF structure acting on the traveling bunch with the vertical force linearly depending on the position along the bunch (zero action at the bunch center). The resulting transversal vertical momentum should much higher than due-to-emittance internal moments in the bunch. Upon passing long enough free space, the different head-to-tail constituents of each bunch will be positioned differently in vertical direction. At this stage a target-cutter is placed, the holes of which are absolutely transparent but the other parts of the target destroy beam components completely. At the same place a vertically focusing lens is placed (focal length is 2 times smaller than RF section to target distance). At the same distance after the target the same RF structure is located, which compensates the vertical moments of bunch components. Hence, at the exit of this section, each driver bunch will be transformed in a seris of microbunches - properly shaped and properly positioned.

Additionally, the way to arrange sequential acceleration, using spiral delay-lines, to reach proportionally higher energy than of driver beam was proposed.

Modest scale experiments to test the approach and to understand related problems more clearly, we hope to start 1997, using the very appropriate BEP booster beam of VEPP-2M complex.

In case of success in the approach development, it would be worth to consider LHC beam (and the beam of the Next Super Collider) to drive such 1 GeV/m plasma linac to get direct proton, antiproton, muon, pion and kaon beams of multiplied energy.

It is worth to study also application of the approach for e^+e^- ($e\gamma$, $\gamma\gamma$) linear collider of ultimate energy, if the ultra-low emittance intense beams plasma acceleration happens to be reachable in principle.

VII. SUPER-THIN INTERNAL TARGETS

Interesting prospects for high luminosity, high sensitivity experiments were found [51], if to use the "super-thin" internal target regime at storage rings, when the stored beam parameters degradation due to multiple interactions with components of the target are suppressed by strong cooling (radiative, electron,...), but the only source of beam losses are single interaction with the target. The regime was tested at VEP-1, and then applied for electron-nuclear interactions at VEPP-2 and VEPP-3, especially for studies of interactions with polarized deuterons. Now the special polarized electron storage ring NEP is prepared as part of VEPP-2 complex at INP, and we do participate actively in the project to arrange polarized electrons experiments in this regime at AmPS (NIKHEF, Amsterdam).

Wide variety of super-thin target experiments with antiprotons and ions under electron cooling were proposed [26,24], most of them are now carried out or in preparation at different labs.

VIII. BEAM DYNAMICS

(SELECTED TOPICS)

Of course, beam physics studies (experiments and theory) through all this years was a core subject in our efforts in high energy accelerators area. Some aspects were mentioned in sections above. Let us just mention several other crucial topics.

8.1. The non-linear dynamics is of very importance for storage rings in general (because of very long life-time needed) and especially for colliders with very strong non-linear high harmonics in beam-beam interaction.

Specifically, of bright impression were the experiments in which transition from "dynamic" to "stochastic" behavior of particle motion in storage ring under multiple resonances influence were studied, and conditions and ways to avoid such transition were tested and proved [52].

8.2. Incoherent beam-beam effects are under continuos study from 1963 - the first collisions at VEP-1 [1,53]. The studies of $\{Q_x, Q_z, Q_s\}$ "maps" gave us not only to operate successfully our first colliders, but together with the development of low-beta insertions and general structures led to the pre-Factory VEPP-2M. Now this understanding is the background for real Factory projects.

It was discovered that in low-beta interaction conditions or at finite angle crossing, longitudinal beam-beam effects can become not only visible, but crucial [54].

Coherent beam-beam effects were under theoretical study and the ways to prevent the consequent luminosity limitation were found [55].

8.3. The single beam coherent instabilities and their curing were at INP always under attention as one of the key issues in reaching high intensities and luminosities.

One of the first effect analyzed was resistive wall phenomenon for single "rigid" bunch, for the first time obtaining stability condition [56].

The unexpected effect was discovered in interaction of bunches with perfectly terminated lines, coupled to the transverse motion of bunches electromagnetically [57]: coherent oscillations become not unstable, but damp very fast _ the higher intensity the faster! This effect is in use in most of our storage rings.

The important effect analyzed and cured was (single) the phase instability of a bunch under interaction with RF cavity (or some parasitic resonant cavity) [58]. Its increment is proportional to

$$R(\Omega_0-\omega_s)-R(\Omega_0+\omega_s) ,$$

where $R(\omega)$ is real part of the longitudinal impedance at frequency ω; Ω_0 is the revolution frequency or its harmonics; ω_s is synchrotron oscillations frequency. Correspondingly, to reach phase stability, the resonant frequencies of all the cavities should be shifted down from the revolution one.

Transverse betatron instability driven by beam interaction with compensating particles (electrons, positive and negative ions) was discovered and investigated for high intensity proton beam (two beam instability) [59]. This instability was damped by negative feed back. Now these instabilities are limiting intensity in many proton storage rings.

The very latest event was the development of advanced theory of transverse head-tail instability with strong mode coupling [60], and design of special kind feedback system, which should rise the instability threshold in this difficult regime. The test experiments are currently under way at LEP collider.

IX. 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. But this subject deserves much more attention than is possible to pay to it here [61].

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.

9.1. The first INP contribution was the invention of special FEL version: the Optical Klystron [1978; 62], especially well suited for storage ring FEL operation. Successful operation of OK at VEPP-3 storage ring [63]. 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 2×10^{-6}.

Now we collaborate actively in the development and construction of dedicated storage ring at Duke University.

9.2. 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 [64]. Many novel concepts are incorporated in the project.

Energy recuperation not only improves 10-20 times wall-plug power efficiency, but converts 50 MW, 50 MeV very radiation difficult and costly installation to reasonably modest one.

One of the most problematic component of any high power laser, the mirror system, is replaced by so-called electron radiation output. The single-pass radiation process is divided in two stages:

- the optical klystron structure and resonant cavity: to introduce proper laser wave length micro-bunching in each electron bunch;
- out of the optical resonator the properly matched long undulator is installed, to radiate coherently about 1% of electron beam energy, with all the optical operations placed far away, where the light beam size is enlarged enough already.

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 efficiencyand high scale power supply for future satellites, including geo-stationary ones.

XII. HIGH POWER TECHNOLOGICAL ELECTRON ACCELERATORS

The development, design, construction and supply of high power, MeV energy range electron accelerators for technological applications [65] 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 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,

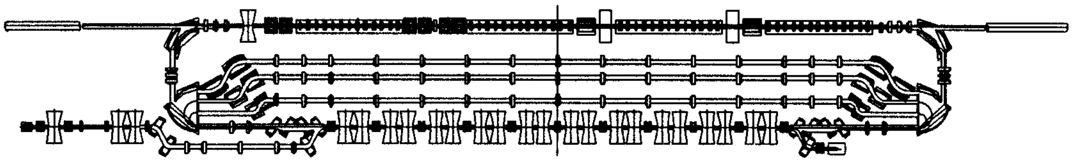

Figure 10. Layout of the Novosibirsk high-power FEL project.

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.

XIII. CONCLUSION.

Unfortunately, this brief history of the accelerator field development at Novosibirsk INP is very incomplete, albeit too lengthy already. 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 and important from VEP-1 to LHC, electrostatic parasitic collision regions orbit separation, 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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