The New Novosibirsk Colliders

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A brief description of electron-positron collider current activity at BINP is presented. The modernized VEPP-4M collider (total energy up to 11 GeV) with new detector KEDR, now in operation, is aimed, first of all, at high precision τ-lepton mass measurements, c-quarkonia studies and two-photon physics in mass range 0.2 – 4 GeV/c^2. The VEPP-2000 collider (total energy up to 2 GeV) is now under final stage of construction. Step-by-step we progress (slowly because of finance problems) in development and construction of Charm/Tau Factory.

1. VEPP-4M COLLIDER

Our Institute was one of the pioneers in collider activities since the very beginning (since 1956). The two – first in the world – colliders started experiments in 1965 – the study of quantum electrodynamics in electron-electron collisions (Princeton-Stanford storage rings, total energy up to 1 GeV, at Stanford, and VEP-1, total energy up to 0.32 GeV, at Novosibirsk [1]). This success gave confidence in prospects of "collider physics" to the world physics community.

The world first electron-positron annihilation experiments were carried out at Novosibirsk collider VEPP-2 in 1967 (total energy up to 1.4 GeV) [1, 2].

Since that time, in Novosibirsk the electron-positron experiments were carried out at VEPP-2M collider [3] (it was the first "pre-factory": the same energy range up to 1.4 GeV, as VEPP-2, but 100 times higher luminosity), which for a quarter of century (1975-2000) was the main supplier of basic information in its energy range [4], and VEPP-4 collider (total energy up to 11 GeV), which was in operation in 1980-1985 [5].

At all four early Novosibirsk colliders many important and interesting experiments were performed (see below).

On my taste, very impressive were high precision mass measurement [6].

Table 1. Progress in accuracy of particle mass measurements by the use of Novosibirsk proposal, development and (mostly) use of resonant depolarization in storage rings in 1970-1980s.

Colliders: VEPP-2M, VEPP-4 (+**Z @ LEP**). Detectors: OLYA, ND, CMD, MD-1

Mesons	**Masses**, MeV/c^2		Year	accur. improv	prosp. KeV
	Particle Data Group	Experimental data			
K^- K^+	493.657±0.020 493.84±0.13	493.670±0.029	1979	5	det.
K^0	497.670±0.13	497.742±0.085 497.661±0.033	1985 1987	4	det.
ω	782.4±0.2	781.78±0.10	1983	2	3
Φ	1019.70±0.24	1019.52±0.13	1975 1978	2	3
Ψ	3097.1±0.9	3096.93±0.09	1980 1981	10	10
Ψ′	3685.3±1.2	3686.00±0.10	1980 1981	10	15
ϒ	9456.2±9.5	9460.57±0.12	1982 1984 1986	**80**	10
ϒ′	10016±10	10023±0.5	1984	20	
ϒ″	10347±10	10355.3±0.5	1984	20	
e^+,e^-	(g–2) comparison: $\Delta\mu'/\mu_0 \leq 1\cdot 10^{-11}$		1987		

As a result: 10^5 precision mass scale from 1 GeV/c^2 to 100 GeV/c^2.

At the moment, experiments in Novosibirsk are in process at deeply modernized collider VEPP-4M (Figure 1) with completely new and advanced detector KEDR (Figure 2) [7].

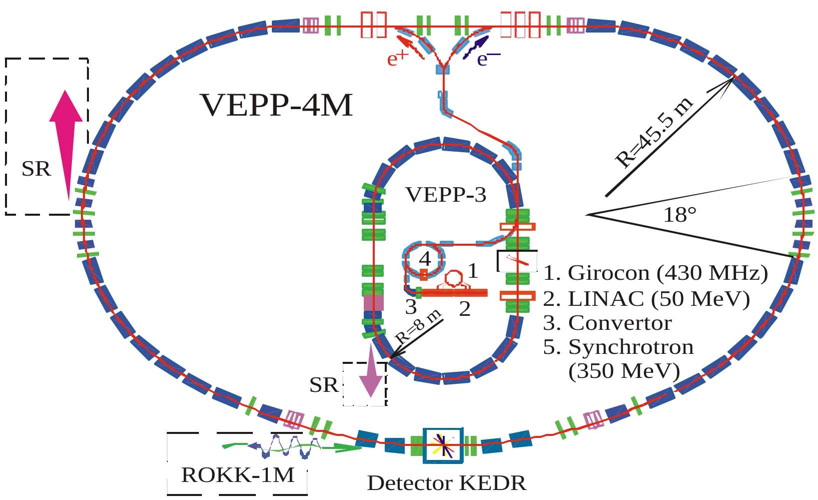

Figure 1. The scheme of the VEPP-4M collider.

The KEDR detector includes, in particular, the barrel electromagnetic calorimeter based on 30 Tones of liquid krypton, with very good both energy deposition and spatial resolution, CsI(Tl) end cup EM calorimeters, large volume aerogel Cherenkov counters, and the superconducting solenoid (magnetic field up to 1.5 T).

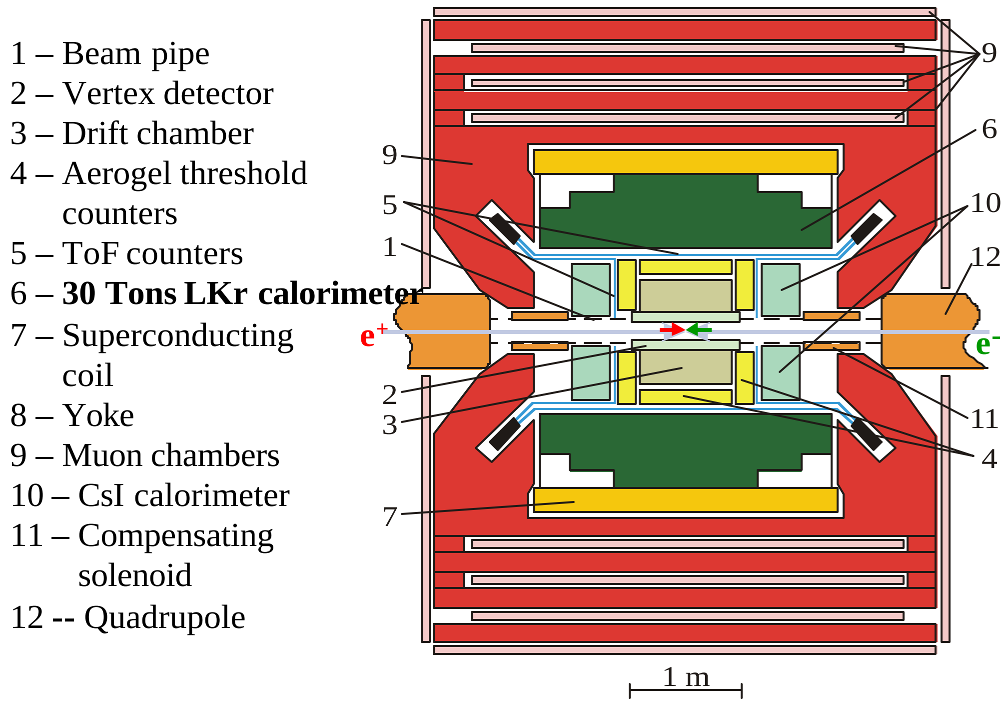

Figure 2. The scheme of the KEDR detector.

Additional specificity of the modern detector system of VEPP-4M collider is the two-arm spectrometer for remaining in event electrons and positrons (Figure 3) [8].

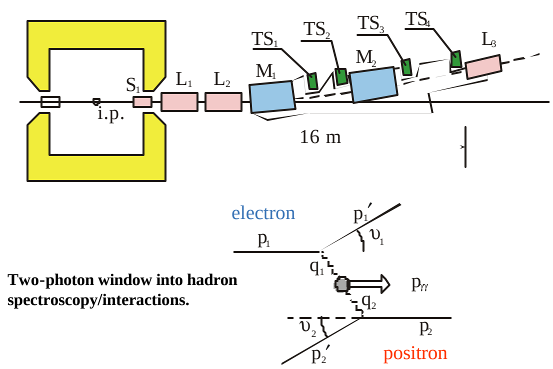

Figure 3. One arm of remaining electrons (positrons) spectrometer.

The recent result, reached at VEPP-4M, was good step in improvement of Ψ and Ψ' mass accuracy – up to $\mathbf{4{\cdot}10^{-6}}$ [9].

The next step should be in τ-lepton mass accuracy improvement by several times.

Then, the energy in the collider will be raised to a higher range and the focus of efforts would be the two-photon physics. The mass resolution for two-photon events, according to simulation and Compton laser scattering tests, should reach – without information from the central detector, just from the two-arm spectrometer – values below 10 MeV/c^2 for masses up to 2.5 GeV/c^2 (Figure 4). It would allow careful study of hadron spectroscopy for two-photon-like quantum numbers.

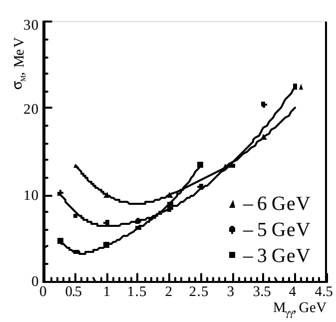

Figure 4. Mass resolution for two-photon events.

Of course, additional information will be collected on total hadron cross-sections, mostly above the Ψ region (to additionally reduce "theoretical" uncertainties in hadron contribution to the muon g-2 value), and on the Y-family physics.

2. VEPP-2000 COLLIDER

The long-term quite successful operation of the VEPP-2M collider gave us the possibility to reduce several times uncertainties in hadron contribution to the muon g-2 value [10]; the main contribution to the hadron contribution errors, which before these experiments were produced by the e^+e^- range below 1.4 GeV (total), as result of VEPP-2M experiments (Figures 5, 6, 7) [11. 12], are so low, that now the contribution to those errors come mainly from energy range 1.4 to 2 GeV (as seen at the same Figures). Additional input came from the reaction $e^+e^- \rightarrow 3\pi$ above 1 GeV (Figure 7) [13]: the cross section of this reaction is very much deviated from the simple vector dominance model, if one includes the well known ρ, ω and ϕ "light" vector mesons only. But, you see, experimental information on cross-sections at somewhat higher energies is very scarce and the errors there (especially between 1.4 GeV and 2 GeV) are very big.

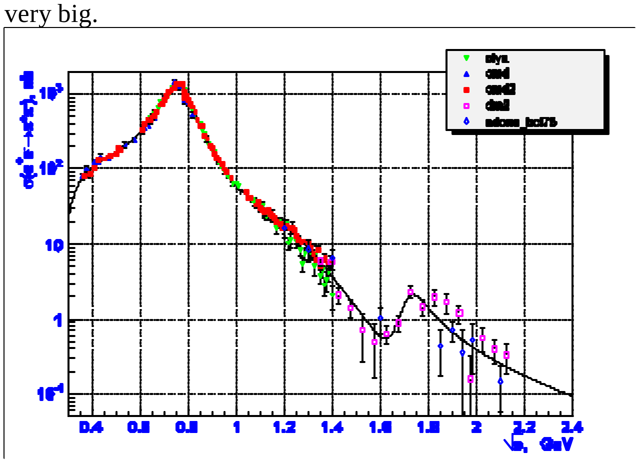

Figure 5. The cross-section of $\pi^+\pi^-$ production in e^+e^- annihilation (up to 1.4 GeV – the VEPP-2M data [11]).

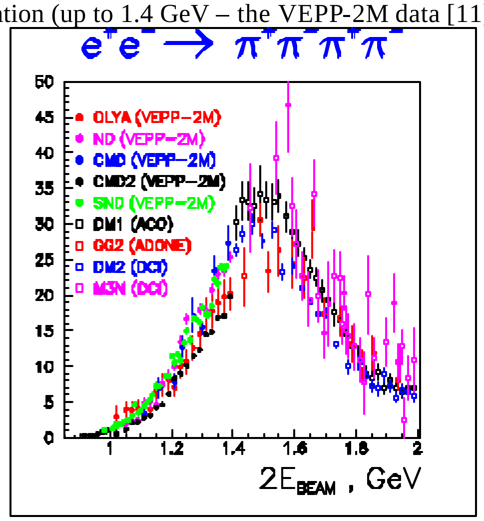

Figure 6. The four pion production – the dominating hadron process in e^+e^- annihilation in 1.2-1.8 GeV region.

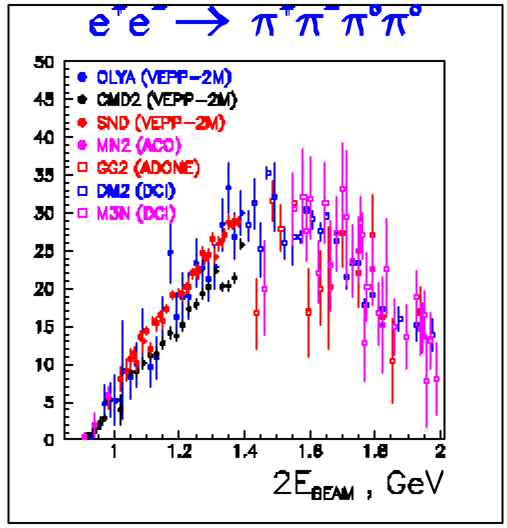

Figure 7. (the same as at Figure 6).

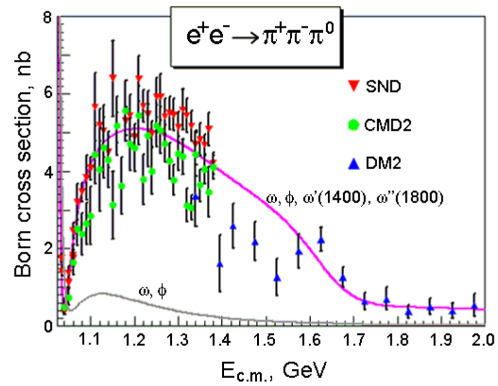

Figure 8. Vector dominance model predictions (the lower curve – if only ω and ϕ are used: the upper one – if additionally ω'(1600) and ω''(1800) – very poorly known! – are taken into account).

Obviously, to study 1.4-2 GeV region is necessary! Such considerations pushed us to the decision to replace VEPP-2M collider with the new collider VEPP-2000 (total energy up to 2 GeV), using a large fraction of VEPP-2M complex infrastructure (Figure 9, 10 and 11, Table 2) [14].

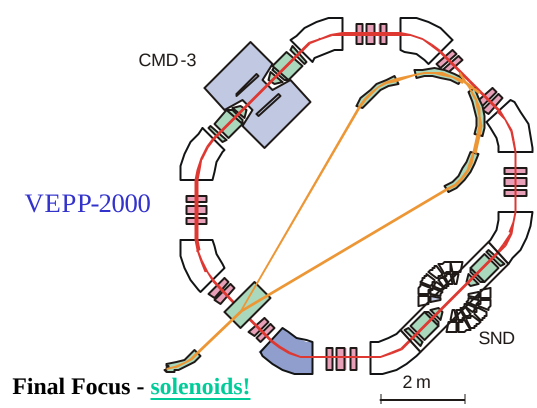

Figure 9. Schematic layout of VEPP-2000 collider.

Table 2. The main parameters of VEPP-2000 (in comparison to VEPP-2M).

	VEPP-2M Em=700 MeV	VEPP-2000 Em=1000 MeV	
E (MeV)	**510**	**510**	**900**
Π (cm)	**1788**	**2438.8**	
I^+, I^- (mA)	**40**	**34**	**200**
$\varepsilon \cdot 10^5$ (cm·rad)	**3**	**0.5**	**1.6**
β_x (cm) β_z (cm)	**40** **5**	**6.3** **6.3**	
ξ_x ξ_z	**0.016** **0.050**	**0.075** **0.075**	**0.075** **0.075**
L ($cm^{-2} s^{-1}$)	**$3 \cdot 10^{30}$**	**$1 \cdot 10^{31}$**	**$1 \cdot 10^{32}$**

Figure 10. The view of VEPP-2000 construction site.

The main accelerator feature of VEPP-2000 is the use of the so called "Round Beams" approach [15].

The approach 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 <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). The tunes $Q_{x,z}$ (for e+e-) closely above integer (for two opposite azimuth interactions per turn) and above half-integer one (for single IR per turn);

e). Low (tunable) synchrotron frequency Q_s.

Items a), b) and c) lead to the conservation of angular momentum in transversal motion, thus reducing 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 attainable beam-beam tune shift ξ_{max}, without detriment to the luminosity. We hope to raise this value, at least, up to 0.1 [16].

The additional useful effect arises due to the simple fact, that the beam-beam focusing for given counting bunch density is 2 times lower for round beams than for smaller dimension of flat beams, thus giving additional rise of the luminosity.

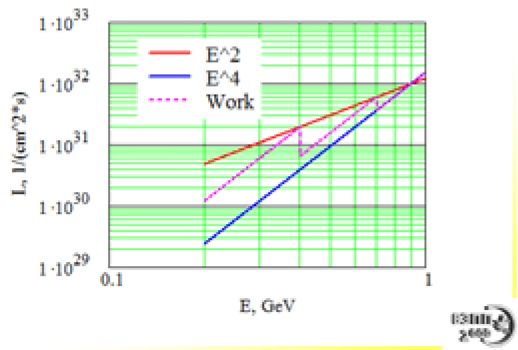

Figure 11. The luminosity of the VEPP-2000 collider in its full energy range.

The VEPP-2000 collider will be equipped with deeply modernized detectors SND [17] and CMD-3 [18] (Figure 12), which, in their initial form, successfully carried out experiments at VEPP-2M.

The main tasks of VEPP-2000 include, also, higher accuracy hadron cross-section measurement, than achieved in record set of experiments at VEPP-2M, in wider energy range – from pion threshold up to 2 GeV (total).

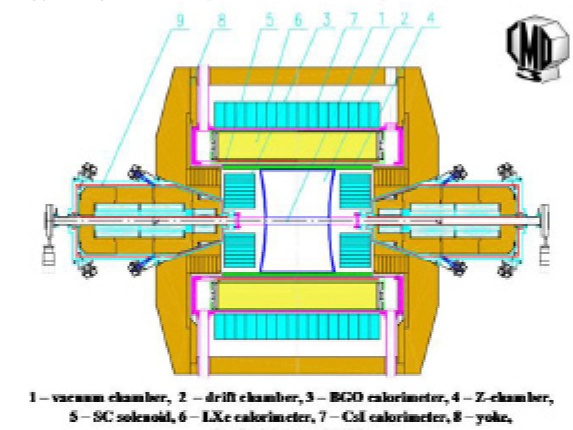

Figure 12. One of the detectors for VEPP-2000 collider – CMD-3.

The next – and quite important – aim for this collider experiments are the measurements of form-factors of protons and, especially interesting, of neutrons, in the time-like momentum transfer near the threshold.

Technically, the most challenging part of the VEPP-2000 collider is the series of the high-field focusing solenoids placed on both sides of each interaction region – with the 13

Tesla magnetic field. Fortunately, using the niobium-tin alloy wires for the internal coil and the niobium-titanium alloy for the outer one, we reached already a slightly higher field.

Our plan is to start the full-scale commissioning of the complex in 2005.

3. VEPP-5 COMPLEX

For many years, in spite of extreme economical difficulties, we proceed to the “Dream Charm/Tau Factory”.

Step-by-step we design and construct systems and installation of the complex, the very sketchy scheme of which is presented in the Figure 13.

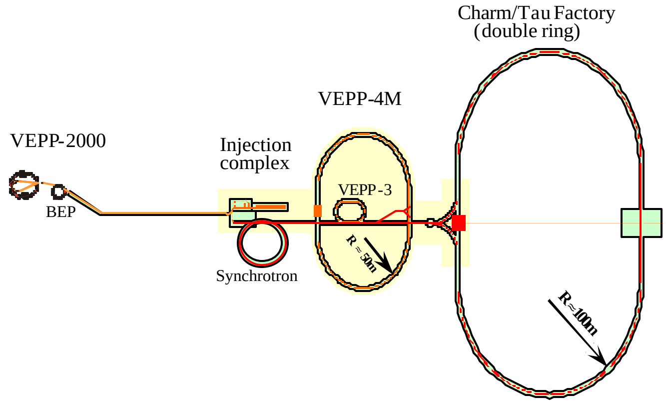

Figure 13. The sketch of Charm/Tau Complex VEPP-5

You can see here, that the new Injector complex [19] will supply with intense and excellently prepared bunches of positrons and electrons the collider in operation VEPP-4M, the collider under construction VEPP-2000, as well as the future Charm/Tau Factory. After completion of the Synchrotron, which would accelerate positrons/electrons from 0.5 GeV to 2.5 GeV (look at Figure 13), it is possible to simplify and modernize all 3 complexes (VEPP-2000, excluding its injector chain completely and injecting beams at the current operation energy; VEPP-4M, injecting beams directly from Synchrotron and accelerating them in VEPP-4M, as now; and inject beams in Charm/Tau Factory at current operation energy). The scheme of the new Injector complex in some details is presented in Figure 14.

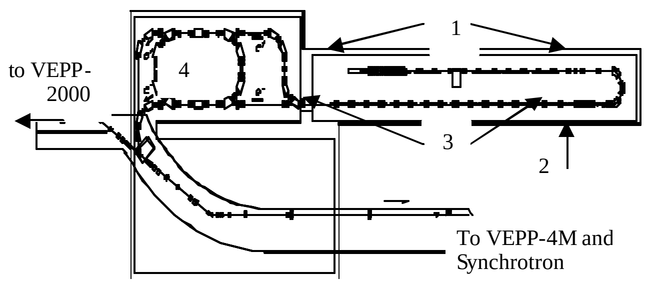

Figure 14. The scheme of new Injector complex (1 – 3 00 MeV electron linac, 2 – converter system, 3 – 500 MeV positron/electron linac, 4 – storage/cooler ring). Productivity >1010 e+/s.

The current stage of the new injector complex is seen in the Figure 15 and 16.

Figure 15. The 500 MeV storage /cooler ring of new Injector complex.

Figure 16. Linacs to produce and accelerate positrons/electrons for the new Injector complex.

3.1.Charm/Tau Factory project

We started development of an "extreme" Charm/Tau Factory project very long ago, and first presented it at SLAC Workshop in 1994 [20] (Figure 17).

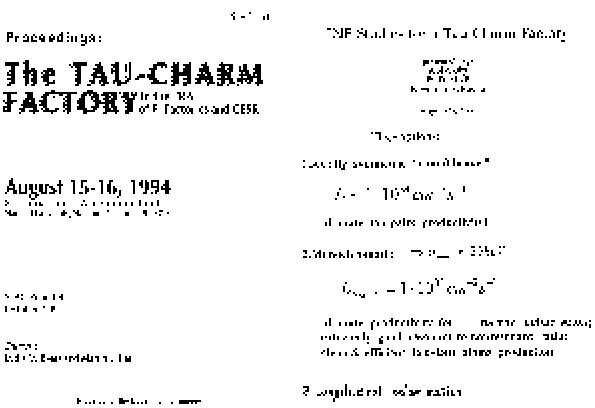

Figure 17. Headlines of INP-1994 presentation at SLAC based Workshop.

It is even funny: all the main aims and numbers of the project remain unchanged up to now.

The Charm/Tau collider consists of two rings (one atop another) of total perimeter about 700 m each with one interaction region, and 2 straight sections 100 m each. The section, closer to injection, would serve for collisions and main detector, and for injection in both rings. In the opposite section high field wigglers would be placed – to enhance orbital damping rate, and (with asymmetric wigglers) – to shorten the polarization time. There would be placed the main RF cavities, also (Figures 18 and 19).

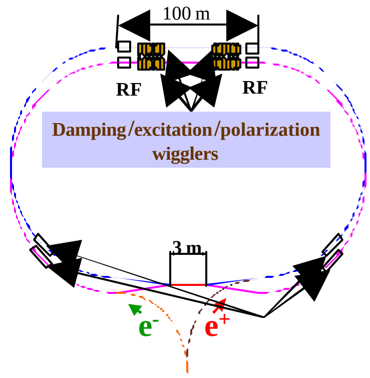

Figure 18. The general scheme of Charm/Tau Factory.

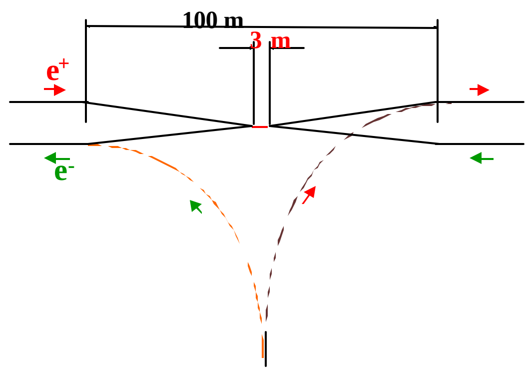

Figure 19. The general scheme of main Interaction Region.

Three main options are foreseen for the Charm/Tau Factory layout and operation.

3.2. The "Highest luminosity" option

To achieve the "highest possible luminosity", we intend to use the "Round Beams" approach (see section 2). We hope to get complete experience with this approach at VEPP-2000.

The schemes of the ring for this option and of Interaction region are presented in Figures 20 and 21.

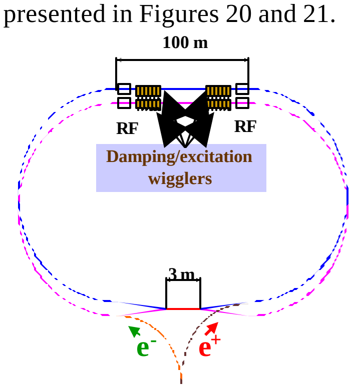

Figure 20. The scheme of the "Highest Luminosity" option.

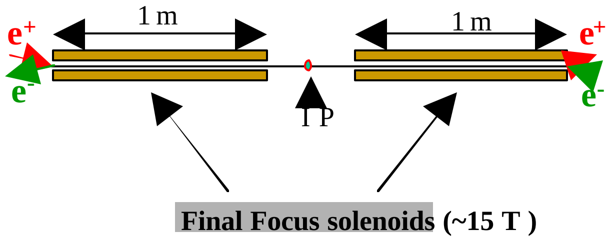

Figure 21. The scheme of Interaction region (option based on using of 15 Tesla solenoids).

Option with solenoids is "the logically simplest". But for this reasonably high energy, maybe, it would be necessary to use a multi-quadrupole-lens optics. The formula for luminosity for Round Beams reads:

$$L_{max} = \frac{4 \cdot \pi c}{r_e^2} \cdot \gamma^2 \cdot \frac{1}{D_{bb}} \cdot \frac{\varepsilon_r}{\beta_{r0}} \cdot \xi_{max}^2 ,$$

(here $\varepsilon_r = \frac{a^2}{\beta}$ - equal transversal emittances).

For 2 GeV per beam, the bunch-to-bunch distance D_{bb}= 5 m, the beta-function at IP, $\beta_{r0,}$ is equal the bunch length σ_{long}=1 cm, achievable beam-beam tune shift is ξ_{max}=0.1 (round beams!), and $\varepsilon_r = 7 \cdot 10^{-6}$ cm (quite modest)

$$L_{max} = 1 \cdot 10^{34}\ cm^{-2}s^{-1}.$$

Number of particles per bunch for this regime is $1 \cdot 10^{11}$. Total number of particles per beam is $1.4 \cdot 10^{13}$.

The total power of synchrotron radiation from wigglers can reach several Megawatts.

Of course, as for other options, all the numbers are shown for orientation only. Future optimization will follow the experience with Round Beams at VEPP-2000, and will use all the experience of so successful B Factories.

3.3. Longitudinally polarized collisions

The possibility to obtain longitudinal polarization – at given azimuth of a storage ring – was first proposed and proved theoretically in Novosibirsk still in 1960s [21]. Since that time, many practical options were considered [22] and realized at HERA for internal target experiment.

The very rough scheme of longitudinally polarized collisions at Charm/Tau Factory is presented in Figure 22. To achieve a fast enough self-polarization and good degree of polarization, the asymmetric wigglers should be long enough and high field poles (with the field of the same direction as in consequent ring) should produce the highest field technically acceptable (of course, both integrals along each wiggler should be zero).

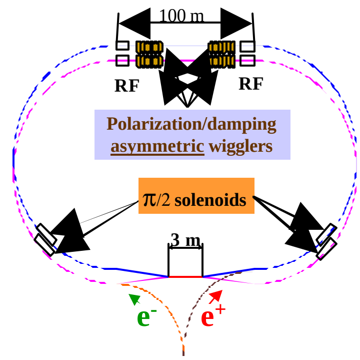

Figure 22. The scheme of longitudinally polarized collisions (proper choice of solenoid signs give possibility to obtain any helicities of electrons and positrons – independently).

When collider operates with opposite helicities close to the threshold of some pairs of spin ½ fermions production (tau-leptons, charmed barions), the degree of polarization of final fermions (parallel to electron and positron orbit direction – fermions are non-relativistic!) will be much better than degree of initial particles:

$$\zeta_{final} = \frac{2\zeta_{ini}}{1+\zeta_{ini}^2} .$$

If, for example, $\xi_{ini1,2}$=0.7, the final fermions would have degree of polarization

$$\xi_{final}=0.94.$$

The luminosity in this case can be evaluated as

$$L_{pol} = \frac{c}{2 \cdot r_e} \cdot \frac{N_{bunch} \gamma \xi_{max}}{D_{bb} \beta_{vert0}} .$$

If we assume ξ_{max}= 0.05 (flat beams!), $N_{bunch}=5 \cdot 10^{10}$, maximal wiggler field 7 Tesla, wiggler total length – 25 m, and all the rest parameters the same as in Option 1, we would get luminosity $L_{pol}=1 \cdot 10^{33}\ cm^{-2}s^{-1}$, polarization time 500s, which is much shorter than luminosity life time, and the polarization degree of each beam becomes better than 70%.

This option should be useful for careful study of decays of polarized tau-leptons (3 millions of tau-lepton pairs per canonical year!) and charmed barions.

3.4. "Monochromatic" option

When narrow J/Ψ and Ψ' mesons were discovered in 1974, immediately appeared the ideas to arrange effective "event mass spread" several times more narrow than this states (few tens of keV) [23].

The idea is simple (Figure 23). If the vertical betatron size $\Delta_{v\text{-}bet}$ in IP is small, but the vertical size due to energy spread and dispersion in this region $\Delta_{v\text{-}disp}$ is much larger, and dispersion functions have opposite signs for electrons and positrons, the effective "event mass spread" will be much smaller – of the order of

$$\Delta M_{eff} = \frac{\Delta_{v-bet}}{\Delta_{v-disp}} \cdot \Delta E_{beam} \cdot \frac{\sqrt{2}}{c^2} .$$

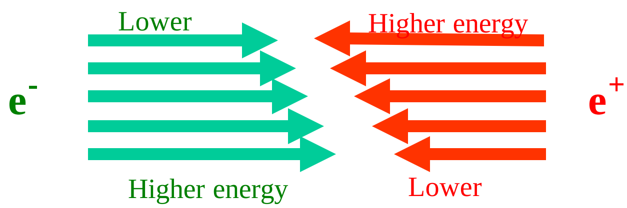

Figure 23. The idea of "monochromatization – the effective mass of events is almost constant.

The idea is simple, and there are many options, which, in principle, can provide success. The optimal option may depend on the experiment requirements, etc. Here we present one of the options, very schematically presented in Figures 24 and 25. The vertical field wigglers at the "technical" straight sections should provide very small horizontal emittance ε_h, and strong damping both in horizontal and vertical betatron oscillations (for both beams, of course). These strong wigglers are needed, mostly, to suppress vertical emittance growth in the region, where vertical energy dispersion is excited (Figure 22). This emittance growth rate would occur due to quantum fluctuations in magnets there, and due to multiple intra-beam scattering in the same region. Of course, the horizontal-vertical coupling in the ring and, especially, in the damping wigglers should be very much suppressed, also.

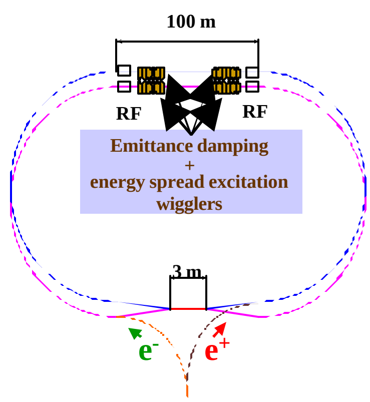

Figure 24. The scheme of preparing of high enough energy spread (to get highest luminosity for mass of events spread needed) and strong enough radiation cooling.

The focusing in the interaction region should be strong, but of special kind: the horizontal beta-function should be very small (say 1 cm) and almost equal to the length of bunches, and the vertical beta-function – modestly small, say, 5 cm (of course the smaller the better, but prospects in this direction are limited in such complicated lattice).

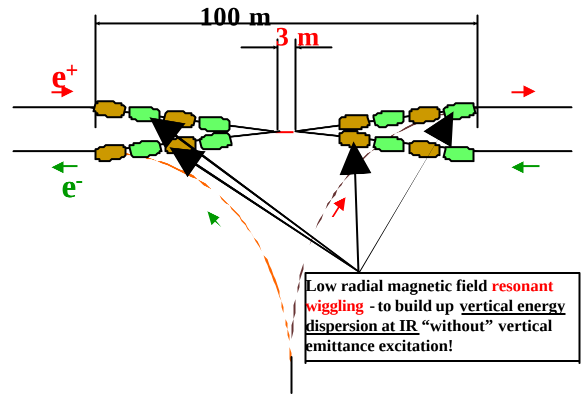

Figure 25. The scheme of resonant excitation of high dispersion at the IP without excitation of vertical betatron size of the beams.

To excite the vertical energy dispersion in IR, the optimal approach seems to be to apply horizontal magnetic field, which sign is alternating in resonance with vertical betatron oscillations. At the first half of these magnets (prior entering final focusing region) dispersion should grow; upon passing this region, the second half of these magnets should eliminate the vertical energy dispersion completely.

For the option described, the maximal achievable luminosity will be about

$$L_{monoMAX} = \\ = \frac{\pi}{8}\cdot\frac{c\cdot e}{\alpha\cdot(m_e c^2)^2}\cdot\frac{\gamma}{D_{bb}}\cdot\beta_{dis}H_w H_{dis}^2 L_{dis}^2\cdot\frac{1}{\beta_{h0}}\cdot\xi_h\xi_v\,,$$

and the effective mass spread of events – about

$$\sigma_{Meff} = 2\sqrt{2}\cdot\frac{(m_e c^2)^2}{e}\cdot\frac{\gamma^2\cdot\sqrt{\varepsilon_v}}{L_{dis}\cdot H_{dis}\cdot\sqrt{\beta_{dis}}}\,.$$

Here:

α=1/137;

β_{dis} – effective beta-function at the excitation section of dispersion;

H_{dis} – magnetic field in dispersive magnets;

L_{dis} – the length of dispersion excitation section (+de-excitation section);

H_w – magnetic field in damping wigglers;

β_{ho} – horizontal beta-function in Interaction Point;

ε_v – resulting vertical emittance (which we need to keep as small as possible, look above);

ξ_h, ξ_v – horizontal and vertical beam-beam tune shifts which are achievable without beams blow-up and without detrimental effect on σ_{Meff}.

Using the approach, layout and estimations described, it seems possible to achieve, for example,

σ_{Meff}= 20 keV with luminosity L= $1\cdot10^{32}$ cm^{-2}s^{-1}

and

σ_{Meff}=5 keV with luminosity L=$1\cdot10^{31}$ cm^{-2}s^{-1}.

The first option would provide an extremely clean and productive generation of J/Ψ mesons deep inside its excitation region.

The second one would allow study the threshold behavior of $\tau^+\tau^-$ pairs (because of electromagnetic attraction of τ leptons, the cross-section starts with 20% of maximal cross-section "jump"); for 5 keV effective mass spread the threshold would be very sharp, correspondingly (Figure 26, Figure 27). Such sharpness would, in principle, not allow extremely sharp definition of of τ lepton mass measurement, but also could expose possible tiny deviation from the Standard Model prediction, thus giving the sign of New Physics.

Moreover, the ττ atoms production would be clearly separated in energy from creation of ττ pairs in continuum; the problem – and difficult problem! – would arise because of the fact: ττ atoms would annihilate "internally" before τ decays (atoms are created dominantly in $^3S(1)$ state, and transition to the long living $^1S(1)$ state is suppressed strongly). It is good challenge to use these atoms for physics – but very interesting.

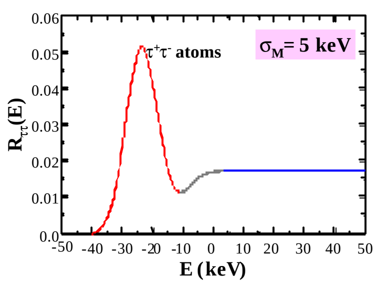

Figure 26. Threshold behavior of t-pairs production (at 5 keV spread tau atoms are very visible)

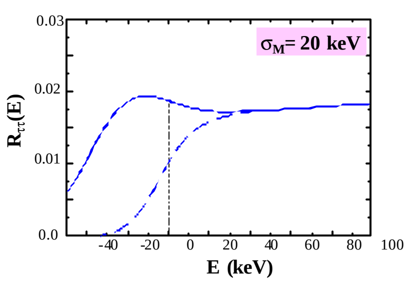

Figure 27. The same process as in Figure 26, but for 20 keV spread – tau-atoms overlap with at threshold production.The study of threshold behavior of the charmed barion-antibarion production could be also quite interesting – when the monochromaticity is very high.

4. CONCLUSION.

The collider-based physics is in progress in the Institute. But, of course, this progress is slow – much slower, than it is possible, in principle, and very much desirable. But especially in the last period, for more than a decade, the State support for research, especially, the basic research, is very, very low. And we (the Institute) try – very actively and with some success, to participate in national (in foreign countries) and international projects – most of them are very interesting for us scientifically – with financing via these projects. We use reasonable fraction of those money to promote our local activity in high energy physics. Good examples of such international activity is our participation in the LHC (the machine and the ATLAS) at CERN – the biggest single "enterprise"; each year it gives us about 1/3 of non-State funding. Other successful and interesting examples are our participation in B Factories activities at KEK and SLAC.

But we definitely hope – and try! – to attract more collaborators from other institutes and countries (and young students of our Universities!) to the current experimental activities and to the on-going projects in our Institute.

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