Particle Accelerators, 1990, Vol. 26, pp. 73–86
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Electron–positron colliders at INP: Status and prospects

A. N. SKRINSKY
Institute of Nuclear Physics, 630090, Novosibirsk, USSR

Experiments with electron-positron colliding beams long ago became an essential part of high energy physics. Fig 1 and Table 1 show two main trends in the development of e^+e^- colliders - energy and luminosity increase. Such experiments started in 1967 in Novosibirsk on the storage ring VEPP-2 where the excitation curve of the ρ-meson resonance in the reaction $e^+e^- \rightarrow \pi^+\pi^-$ was obtained. The maximum luminosity achieved on that collider was 5.10^{28} $cm^{-2}s^{-1}$ only. For comparison, 1.10^{32} $cm^{-2}s^{-1}$ has already been achieved on CESR at Cornell, whereas at future electron-positron factories it is hoped to approach the value 1.10^{34} $cm^{-2}s^{-1}$. The rate of energy increase is also high. This year a very important stage has been passed - SLC and LEP have observed the first production of Z^0-bosons in e^+e^- collisions. On behalf of the whole accelerator community I would like to congratulate SLAC and CERN laboratories on their success. Further considerable energy increase is inevitably related to a transfer from circular electron-positron colliders to linear ones. The obvious need in international collaboration on development of linear colliders becomes the acquisition of practical putlines and the first joint step will be the construction of an experimental installation for operation with beams of submicrometer transverse size. Such an installation is being planned by the SLAC-INP-KEK-CERN collaboration using SLC as a base.

Table 1

Name	**Location**	**Total Energy** (GeV)	**Luminosity** ($cm^{-2}s^{-1}$)	**First experiment**	**Shut-down**
VEPP-2	USSR, Novosibirsk	1.35	3×10^{28}	1967	1970
ACO	France	1.1	1×10^{29}	1968	1974
ADONE	Italy	3.2	6×10^{29}	1969	1975
SPEAR	USA	8.4	2×10^{31}	1973	
VEPP-2M	USSR, Novosibirsk	1.4	4×10^{30}	1974	1987
DORIS	BRD	10.2	3×10^{31}	1974	
DCI	France	3.1	2×10^{30}	1976	1984
PETRA	BRD	46	2×10^{31}	1978	1987
CESR	USA	11.2	1×10^{32}	1979	
VEPP-4	USSR,Novosibirsk	10.2	6×10^{30}	1980	1985
PEP	USA	30	2×10^{31}	1980	
TRISTAN	Japan	60	(8×10^{31})	1987	
SLC	USA	100	(6×10^{30})	1989	
BEPC	China	5.6	(2×10^{31})	1988	
VEPP-2MM	USSR, Novosibirsk	1.4	(3×10^{31})	(1990)	
LEP-1	CERN	100	(1×10^{31})	1989	
VEPP-4M	USSR, Novosibirsk	12	(1×10^{32})	(1990)	
LEP-2	CERN	200	(2×10^{31})	(1992)	
VEPP-5	USSR, Novosibirsk	14	(1×10^{34})	(1994)	
VLEPP	USSR, Protvino	1000	(1×10^{33})	(1996)	
VLEPP	USSR, Protvino	2000	(1×10^{33})	(1998)	
TLC	USA	1000	(1×10^{33})		
CLIC	CERN	2000	(1×10^{33})		

It should be kept in mind that increase of energy and luminosity of e^+e^- colliders does not exhaust all the problems of their development. The use of transversely polarized beams enabled the accuracy of particle mass measurements to be improved by orders of magnitude[1] (Table 2). Longitudinally polarized colliding beams will make the physics potential of e^+e^- experiments considerably higher. Also very interesting is the improvement of monochromaticity of the colliding beams,[2] which is rather high, even without special efforts.

Table 2

Particle mass (MeV)

Particle	**World average value**	**Experimental results**	**Accuracy improvement**
K^-	493.657 ± 0.020		
K^+	493.84 ± 0.13	493.670 ± 0.029	5
K^0	497.67 ± 0.13	497.661 ± 0.033	4
ω	782.4 ± 0.2	781.78 ± 0.10	2
ϕ	1 019.70 ± 0.24	1 019.52 ± 0.13	2.5
ψ	3 097.1 ± 0.9	3 096.93 ± 0.09	10
ψ'	3 685.3 ± 1.2	3 686.00 ± 0.10	10
Υ	9 456.2 ± 9.5	9 460.59 ± 0.12	80
Υ'	10 016.0 ± 10.0	10 023.6 ± 0.5	20
Υ''	10 347.0 ± 10.0	10 355.3 ± 0.5	2

Consider the status of e^+e^- facilities now available in the Institute of Nuclear Physics (INP). Over 15 years the VEPP-2M collider provided luminosity by more than one order of magnitude higher than total luminosity of all other colliders in this energy range (up to 1.4 GeV in total). The start of operation of a new booster BEP will enable further increase of the efficient luminosity by several times (Fig 3). Our experience with the VEPP-2M facility allowed us to find a way of increasing luminosity in the region of the φ-meson resonance by two more orders. The Novosibirsk ϕ-factory (Fig 4) will provide about 10^{11} pairs of K_SK_L mesons per year.[3] This will enable the improvement of the accuracy of the most important parameters of CP-violation in the K_L decays by one order and K_S decays by five orders. This very problem of studying CP-violation is a main stimulus for the development of the ϕ-factory, but of course new possibilities will open for investigating rare and, at the same time, interesting decay modes of φ- and K-mesons.

The special features of the ϕ-factory under development are: a) the orbit shape, resembling a figure 8, enables one to combine both interaction points of each pair of e^+e^- bunches in the region of one detector; b) focusing in the interaction region using superconducting solenoids providing symmetric focusing with β-functions less than 1 cm; c) use of superconducting bending magnets ensures low damping time; d) the choice of the focusing structure providing equal beam size independently excited by quantum fluctuations in both transverse degrees of freedom; and e) possibility of operation with two or three bunches in each beam with electrostatic separation in all undesirable interaction points.

The main parameters of the ϕ-factory compared to VEPP-2M are presented in Table 3. Of special interest is the operation mode with two bunches per beam having identical parameters. If trajectories are accurately combined, this mode provides precise compensation of coherent electromagnetic bunch fields before the collision. One should of course study possible instabilities, but it seems quite probable to surpass by several times a tune shift limit because of beam-beam interactions and have a quadratic gain in luminosity (if one can provide a necessary number of particles stably stored in each beam).

Table 3 – Basic parameters of the ϕ-factory and beams

Parameters		ϕ-factory	VEPP-2M with wiggler
Circumference, c (m)		28.0	17.88
Accelerating voltage frequency, f_0 (MHz)		700	200
Momentum compaction factor, α		0.003	0.167
Emittances,	ϵ_{x0} (cm rad)	2.8×10^{-5}	4.6×10^{-5}
	ϵ_{z0} (cm rad)	2.8×10^{-5}	5.5×10^{-7}
Radiative energy loss per turn, ΔE_0 (keV)		40	9.1
Dimensionless damping decrements between interaction points,	δ_z	2.3×10^{-5}	0.44×10^{-5}
	δ_x	2.3×10^{-5}	0.38×10^{-5}
	δ_s	4.7×10^{-5}	0.94×10^{-5}
RMS energy spread in the beam, $\sigma(\Delta E/E)$		5×10^{-4}	6×10^{-4}
β-Functions at the IP,	β_z (cm)	0.5	4.5
	β_x (cm)	0.5	48
RMS longitudinal size, σ_s (cm)		0.4	3.5
Betatron tunes,	ν_z	6.05	3.09
	ν_x	6.05	3.06
No particles in bunch, N (e^+,e^-)		8.9×10^{10}	3.7×10^{10}
Space charge parameters,	ξ_z	0.07	0.05
	ξ_x	0.07	0.02
Luminosity in single bunch mode, $\mathscr{L}_{max}$ ($cm^{-2}s^{-1}$)		1×10^{33}	1×10^{33}
Luminosity in three bunch mode, $\mathscr{L}_{max}$ ($cm^{-2}s^{-1}$)		3×10^{31}	

To attain the maximum luminosity of the ϕ-factory one should provide a high injection rate of positrons (and correspondingly electrons) directly at the energy of experiment. One should keep in mind that the process of single bremsstrahlung will result in losing about 10^9 e^+/s at the luminosity of 3.10^{33} $cm^{-2}s^{-1}$. It is desirable to have injection by small portions at ultimately low perturbations of already stored particles. The losses during injection must be small and short in time to provide nearly continuous detector operation. This results in serious requirements for the injection systems and we therefore plan to make a ϕ-factory a part of the facility in design now, providing injection of high quality intense beams of electrons and positrons to the existing VEPP-4M collider and the ϕ-factory VEPP-5.

At present, large modernization of the VEPP-4M (Fig 5, Table 4) is near completion, and has several aims. First, the luminosity of the storage ring will be considerably higher - instead of 6.10^{30} $cm^{-2}s^{-1}$ achieved earlier it should exceed 1.10^{32} $cm^{-2}s^{-1}$ (Fig 6). However, even after such modernization the luminosity of this collider will not exceed that already achieved at CESR. Therefore much attention is going into the construction of the KEDR detector developed together with Italian physicists. Some of its parameters, we believe, will surpass those of other detectors, mainly due to the use of liquid for the electromagnetic calorimeter.

Table 4 – VEPP-4M

Energy	4-6 GeV	*RF system*	
Circumference	36 604 cm	Wavelength	165 cm
Revolution frequency	819.01 kHz	Harmonic number	222
		Maximum circumferential voltage	9 MV
Periodic cell		Separatriss energy size	2%
Focusing structure	FODO	Synchrotron tune	0.03
Mean radius	4 549.587 cm	Bunch length, σ_l	4 cm
Bending radius	3 453.6 cm	RF power for beams	400 kW
Horizontal aperture	6 cm	RF power in the cavities	800 kW
Vertical aperture	2.7 cm		
Horizontal β-function	1 105 cm		
Vertical β-function	1 442 cm	*Interaction point*	
Dispersion function	121 cm	Horizontal β-function	74.5 cm
		Vertical β-function	5 cm
Working point Q_x, Q_z	8.53, 7.57	Dispersion function	80 cm
Momentum compaction factor	0.017	Beam sizes, σ_x, σ_z	1 040 μm, 7 μm
		Linear beam-beam Q shift, ϵ_z, ϵ_x	0.05, 0.005
For beam energy 6 GeV		No particles in bunch	2×10^{11}
Synchrotron radiation loss per turn	4 MeV	No bunches	2
Horizontal emittance	4.10^{-5}	Beam current	50 mA
Vertical emittance	10^{-7}		
Energy spread	1.1×10^{-3}		
Damping time	2 ms	Luminosity	7×10^{31}

There is one field in which the VEPP-4M collider is without equal - that of two-photon physics (in the range of two photon masses up to 4 GeV). Special structure of the entire interaction region (Fig 7) allows detection of electrons and positrons moving at small angles with respect to the initial directions in the two-photon reaction

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

with energy and angular resolution providing X-mass measurement with accuracy about 10 MeV, close to a natural energy spread of the beams. Detecting also the produced system X in the central detector, one obtains the picture of hadronic production with photon-photon colliding beams similar to that in Fig 8.

Further relatively small changes of the interaction region (Fig 9) will allow experiments with longitudinally polarized e^+e^-. If one studies the e^+ and e^- helicity dependence of hadronic cross-sections giving information about weak interactions of b-quarks, one of the main problems is to decrease systematic uncertainties. The total contribution of helicities to the cross-section is about 1% and one should measure it with an accuracy not worse than, say, 20%. Therefore one should provide identical conditions for the orbital motion of the e^+ and e^- bunches for events with different given helicity (parallel data taking, constant external fields, equalized number of particles in the bunches). Favorable conditions for such experiments will arise after construction of the new injection facility when electrons and positrons will be injected just at the energy of experiment.

The whole facility will look like Fig 10. The injector part consists of two linacs with a wavelength of 10 cm and an energy of 500 MeV (or one 500 MeV linac, passing e^- and then e^+) as well as the cooling storage ring for the energy 510 MeV. It will provide low-emittance electron and positron bunches at a rate of 10^{10} e^+,e^- per second.

A part of the cycles will end by injection into the ϕ-factory, in other cycles particles will be accelerated in the main linac with a wavelength about 2 cm, acceleration rate of 100 MeV/m and a total energy up to 8 GeV. Units developing for the linear collider VLEPP will serve as linac elements. After acceleration up to the energy of experiment bunches will be injected into VEPP-4M or VEPP-5.

VEPP-5 is a B-factory with a center-of-mass energy up to 11-13 GeV and luminosity close to 1.10^{34} $cm^{-2}s^{-1}$. To achieve such a luminosity one should have two separate rings for electrons and positrons. The required values of bunch parameters can be roughly estimated from the usual formula

$$\mathcal{L}_{max} \approx \frac{c}{r_e} \cdot \frac{\gamma N_b \xi_{max}}{\sigma_l L_b}$$

where N_b is the number of particles in each bunch, σ_l is a bunch halflength, L_b is a distance between bunches, ξ_{max} is a maximum allowed tune shift.

Two alternative variants are under consideration. In one case energies of both beams are equal, their separation in the vertical direction is performed by an electrostatic field applied already beyond the interaction region after final focusing lenses. Rings are located one over another in the tunnel.[4] A minimum distance between the bunches can be made, in this case 40 m; the number of particles in each bunch should be correspondingly very high and close to 10^{12}, σ_l about 1 cm.

In the second variant, beam energies differ from one another, e.g. at Υ (4S) the positron and electron energies are 7 and 4 GeV respectively. Beam separation is now performed by the magnetic field in a horizontal plane, and the low energy ring is installed inside the high energy one in the same tunnel.[5] In this case the distance between the bunches can be by more than one order lower if one provides good separation of the bunches in all extra interaction points. Correspondingly it is much easier to obtain required values of bunch parameters. A possible lattice of the interaction region is shown in Fig 11. Different beam energies are also attractive for studies of CP-violation in some processes with B-mesons.

Serious attention is also drawn to the development of such collider structures which would make higher the effective monochromatization of the colliding beams.[4] In B-meson studies this helps to select interesting events. Operating at narrow resonances Υ (1S), Υ (2S), Υ (3S) and at not yet discovered D-states, this provides better signal to noise ratio as well as higher collider productivity. A special operation mode at low energy will allow additional monochromatization to be achieved making possible a search for irregularities in the structure of ψ and ψ' resonances. The main parameters of the VEPP-5 project are listed in Table 5.

However, the major direction of our Institute's activities in the field of electron-positron colliders is design and construction of the linear collider VLEPP. Already at the end of the 1960s it was clear to us in Novosibirsk that to reach energies of hundreds of gigaelectronvolts, one should proceed to linear colliders. These considerations were reported in 1971 at the *International Seminar on Perspectives of High Energy Physics* in Morges, Switzerland. At that time use of the superconducting linacs with energy recuperation at the second part of the linac seemed more promising. However, we later moved to using pulsed linacs with normal conductivity (a variant also discussed in Morges). In 1978, at the international seminar in Novosibirsk, devoted to the memory of A M Budker, we presented the selfconsistent physical project of the linear collider.[6,7] Its main points were: a) acceleration of a single bunch with correct matching of the number of particles, bunch length, wavelength and acceleration rate allows a high efficiency (dozens per cent) in transforming the energy accumulated in the accelerating structure into the beam energy at a good monochromaticity of about 1%; b) acceleration rate can be as high as 100 MeV/m which was several times larger than usual at that time; c) transverse instability, arising during the acceleration of even a single bunch in linac, can be efficiently suppressed by the introduction of a correct energy gradient along the bunch, this effect is now referred to as BNS damping,[8] with its compensation at the end of acceleration; d) during the collision of intensive bunches coherent two-bunch instability can arise - this effect limits the density in the colliding bunches at a given energy; e) the fields in the intensive bunches are so high at the required micrometer cross-sections of the beams in the interaction region that the radiation in the coherent field of the counter bunch (beamsstrahlung) can become large and require the use of flat bunches; f) required intensive and super-low-emittance bunches can really be obtained in cooling storage rings at an energy of about 1 GeV; and g) used bunches of high energy electrons and positrons can provide recuperation of the bunches for the next cycle via conversion.

Table 5 – Parameters of asymmetric 4 × 7 GeV B–factory

Beam energy (GeV)		7		4
Circumference (m)		600		588
Emittance (m.rad) × 10^{-10},	ϵ_h	250		80
	ϵ_v	2.5		2.2
Energy spread (10^{-3})		0.9		0.9
Damping partition number,	G_s	1.8		1.3
	G_h	1.2		1.7
Bending radius (m)		50		24
Betatron frequency,	Q_v	24		25
	Q_h	25		26
Synchrotron frequency, Q_s		0.024		0.018
Momentum compaction (10^{-3})		2.8		2.1
Accelerating voltage (MV)		10		4
Bunch length, σ (cm)		1		1
Synchrotron radiation power (MW)		3.2		0.9
Crossing parameters (cm)	β_h	40		50
	ψ	50		40
	β_v	1		1
Particles per bunch, 10^{10}		6		8
No bunches		150		147
Tune shift,	ζ_v	0.05		0.05
	ζ_h	0.008		0.009
Center of mass energy (GeV)			10.6	
Center of mass energy spread, σ_v (MeV)			1.4	
Peak luminosity (10^{33} $cm^{-2}s^{-1}$)			5	
No interaction regions			2	

Further development of this project kept these main features, adding to them a possibility of obtaining polarized electrons and positrons, refining details and optimizing the whole project. The current scheme of VLEPP is shown in Fig 12, and the main parameters are listed in Table 6.

Table 6 – VLEPP

	Stage I	**Stage II**
$2 \times E$ (GeV)	2×500	$2 \times 1\,000$
$\mathscr{L}$ ($\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	10^{33}	10^{34}
$2 \times l$ (km)	2×6	2×12
$\bar{P}$ (MW)	100	200
λ (cm)	2.1	2.1
f (Hz)	100	100
n^+, n^-	$(1 \div 2) \times 10^{11}$	$(1 \div 2) \times 10^{11}$
t	1996	1998

Final focus test facility collaboration: SLAC–KEK–INP(–CERN)

In 1987, an important event occurred - the state decision was taken about the construction of the electron-positron linear collider VLEPP for an energy of 1 000 GeV × 1 000 GeV. This facility will be constructed at Protvino near the accelerator UNK which is under construction now. To this end a Branch of the INP has been created there and V E Balakin has been appointed its director. The decision to construct the VLEPP there is related to the possibility of using construction facilities already developed for UNK. Besides that one can try in future use the co-operation of UNK and VLEPP for creating electron-proton colliding beams with an energy up to 2 TeV × 3 TeV and high enough luminosity.

However, the main efforts in the development of the VLEPP components as well as the technology of their serial production will be concentrated in Novosibirsk.

All electron-positron facilities of the INP under construction and design are orientated at wide collaboration both inside and outside the country. We invite our colleagues from all interested centers and laboratories to participate in this work at all possible stages - collider development and construction; construction of detectors; data recording and analysis.

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8. V E Balakin et al. *Proc. VIth All-Union Conf. Charged Particle Accelerators*, vol 1, p 143, Dubna, 1979.

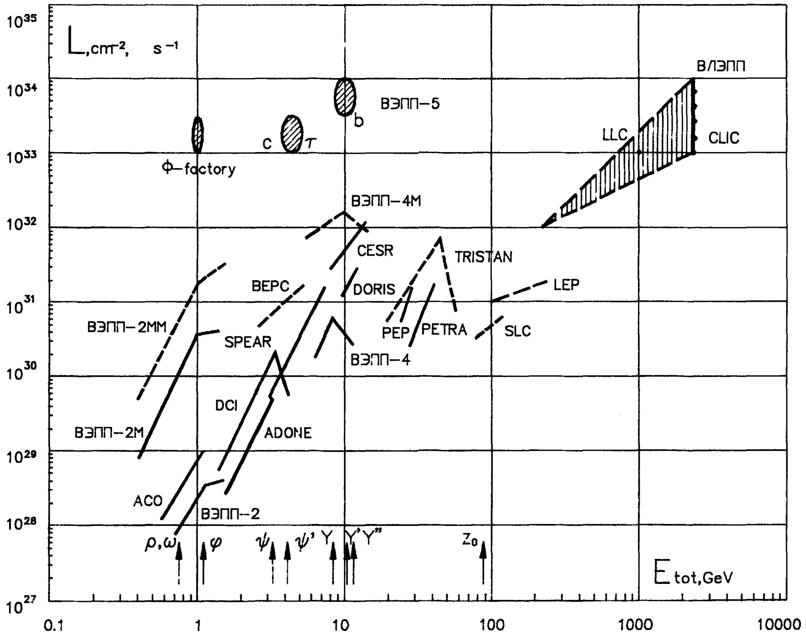


Fig.1.

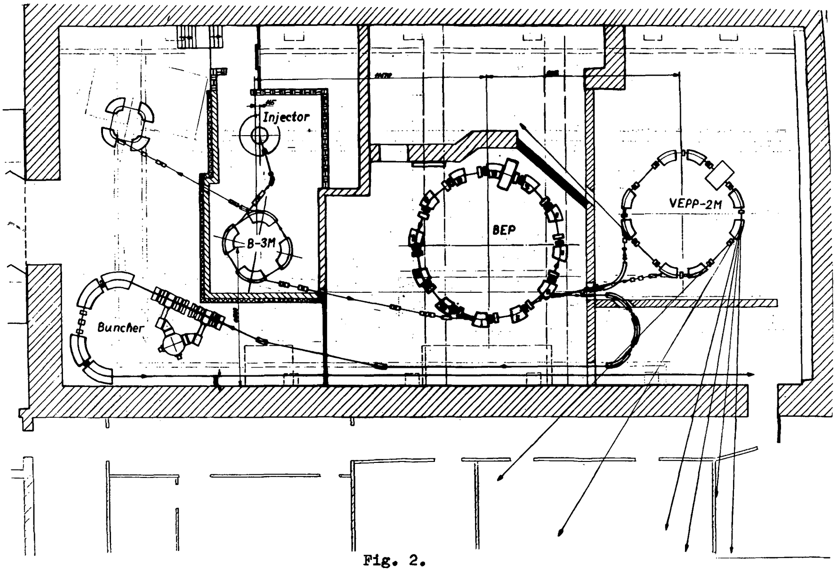
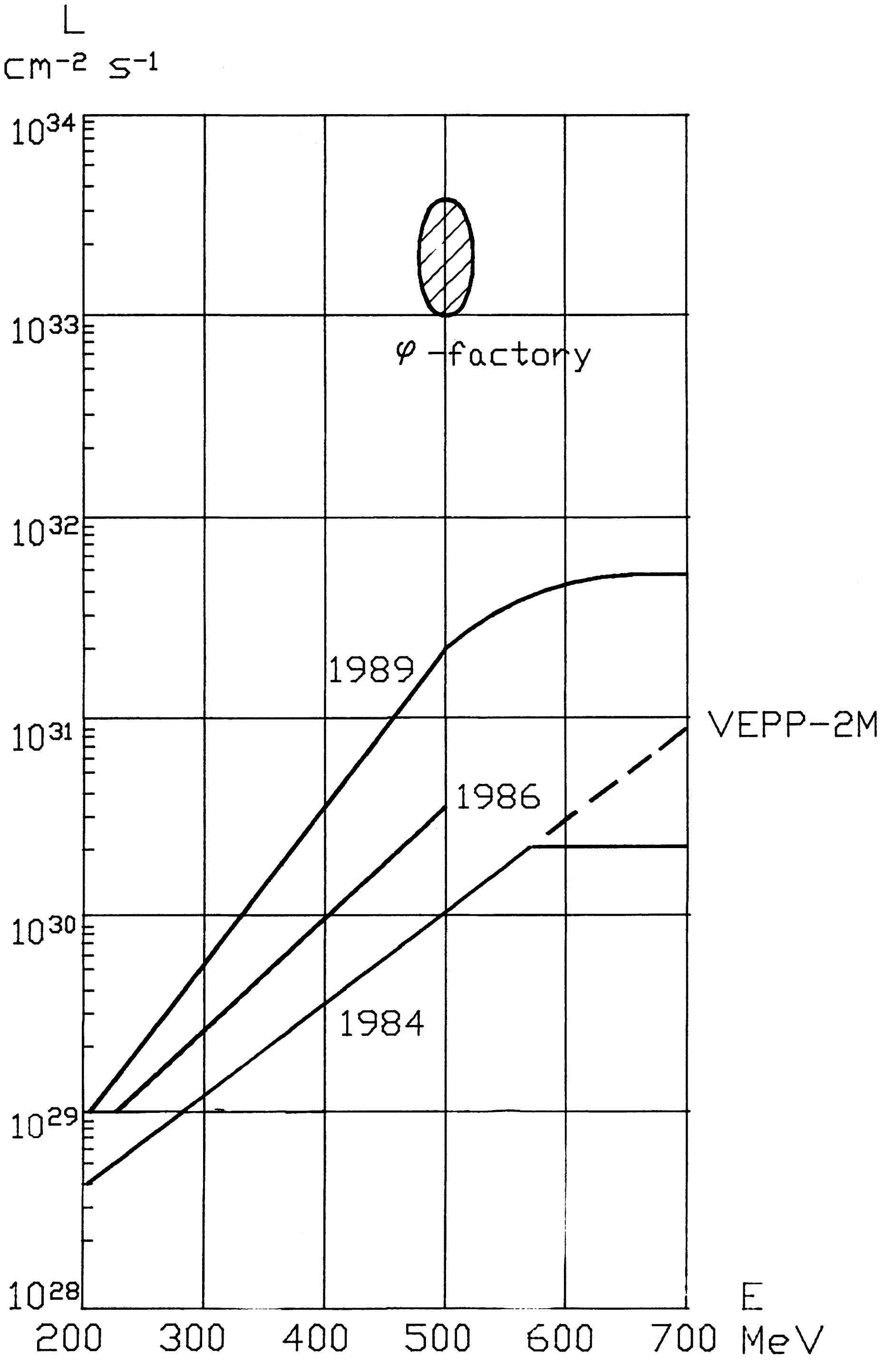


Fig. 2.


L
cm^{-2} s^{-1}
10^{34}
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10^{31}
10^{30}
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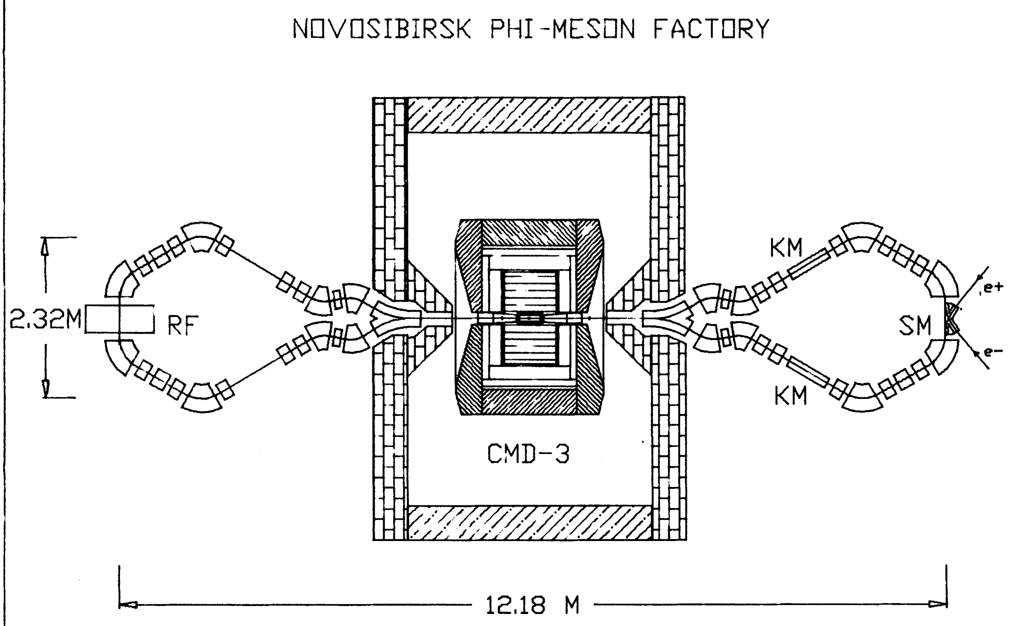
φ -factory
1989
1986
1984
VEPP-2M
E
200
300
400
500
600
700
MeV

Fig.3.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KM
SM
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e-
CMD-3
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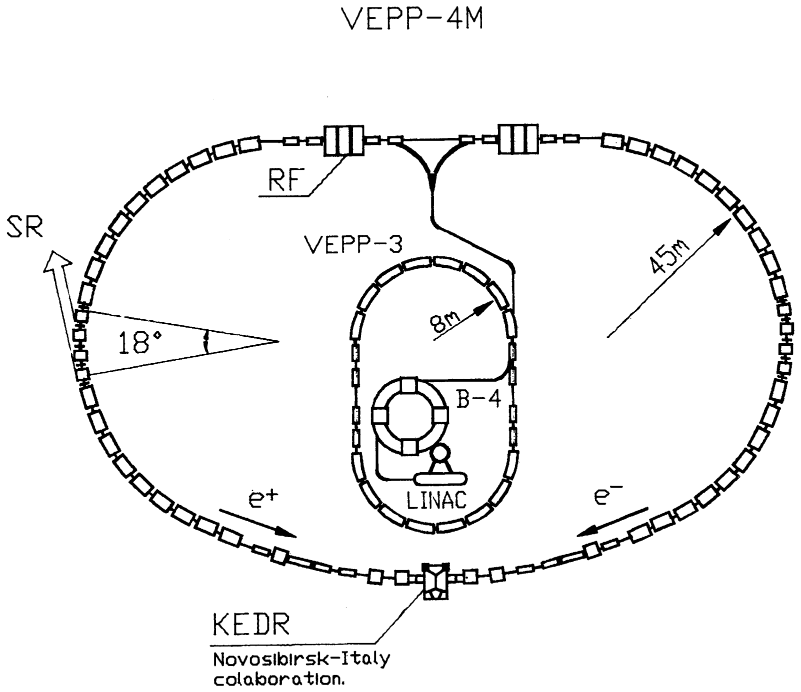
Fig.4.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RF
SR
VEPP-3
45m
8m
18°
B-4
LINAC
e+
e−
KEDR
Novosibirsk-Italy
colaboration.

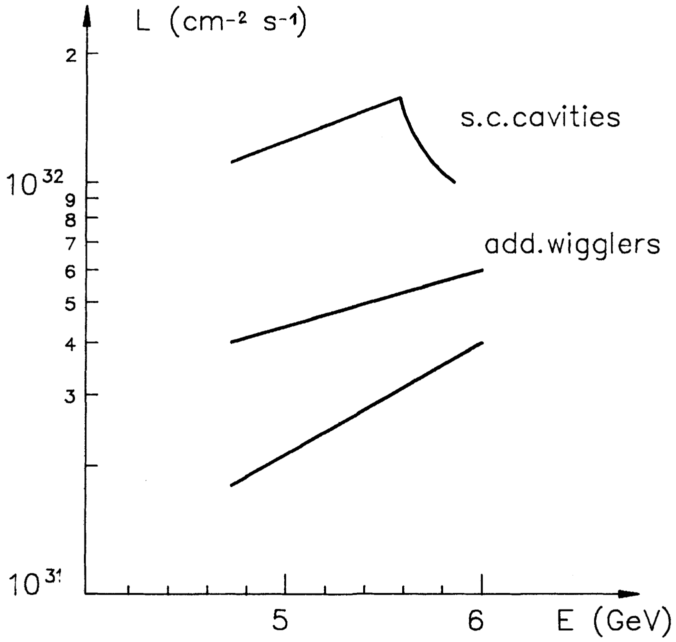


Fig.6.

Lay-out of the tagging sistem for VEPP-4M.
Electrons are detected in the energy range
$0{,}4E_0 < E < 0{,}97E_0$, $\theta < 10$mrad.
Energy resolution $\sigma^E/_E \approx 2\ 10^{-3}$

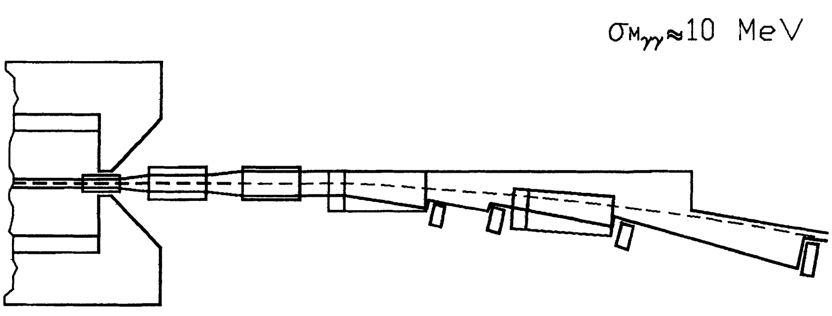
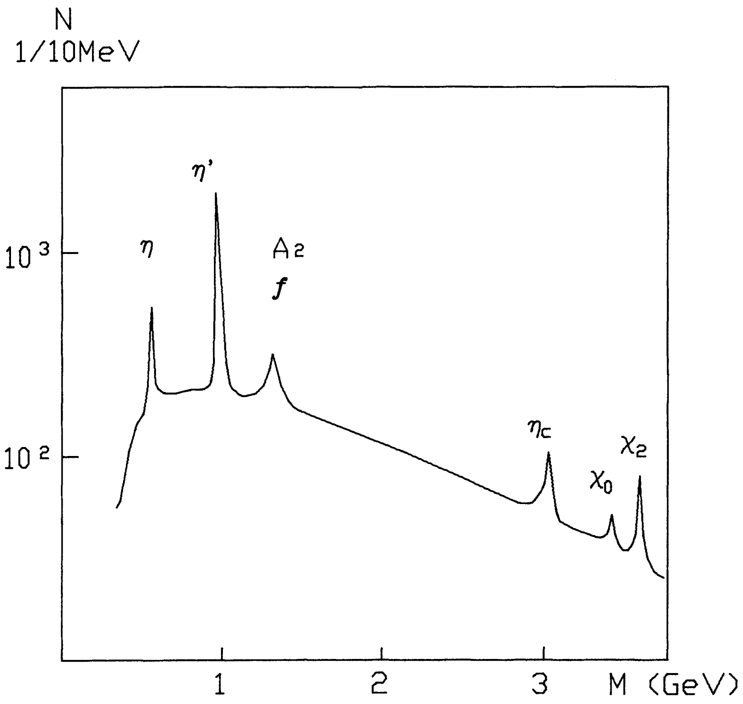


Fig.7.



The number of events expected at the integrated luminosity of 100 pb-1

Fig.8.

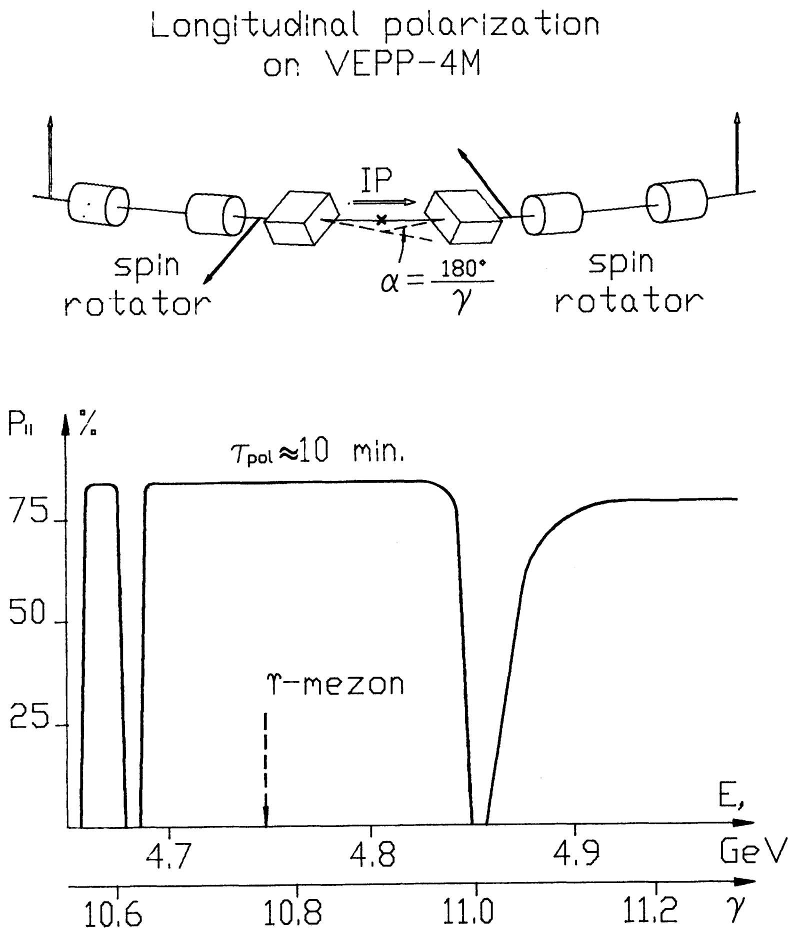


Fig.9.

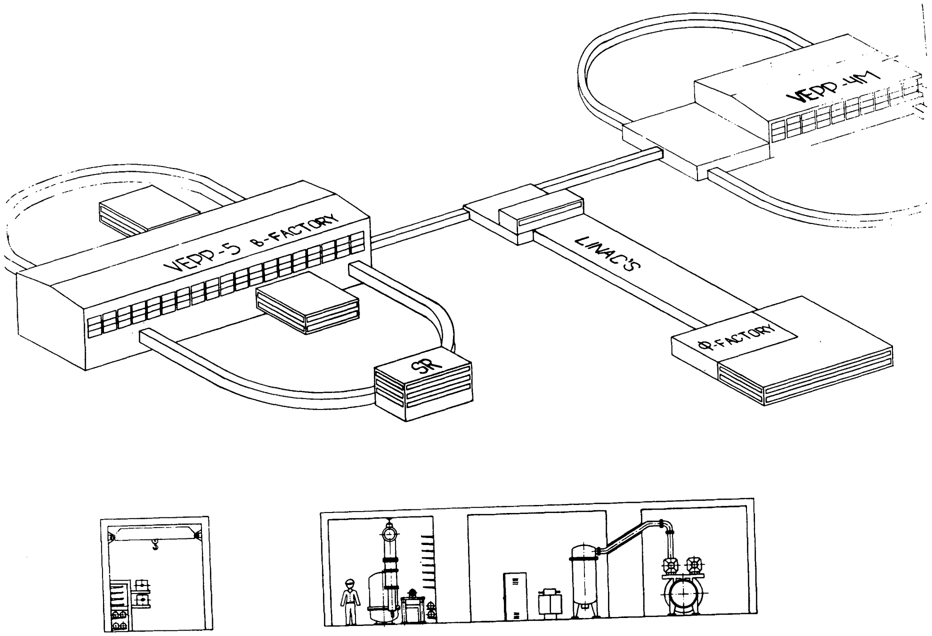
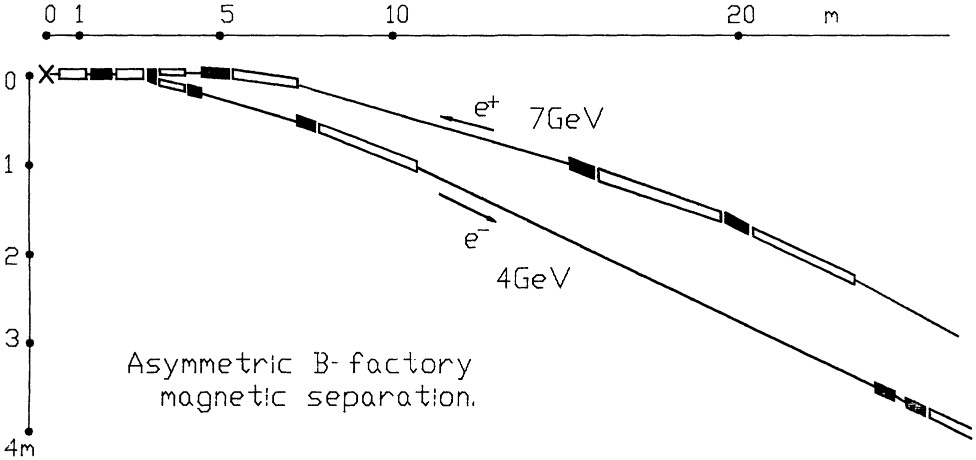

VEPP-4M
VEPP-5 B-FACTORY
LINAC'S
SR
Φ-FACTORY

Fig. 10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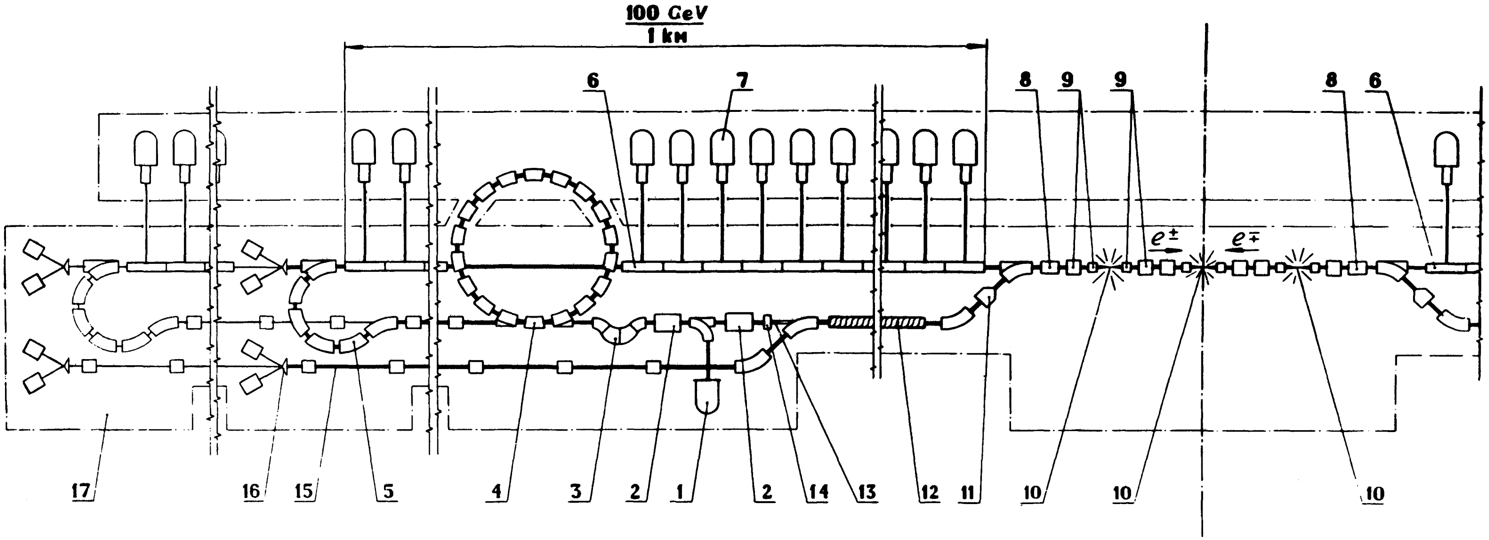
0
1
2
3
4m
e+ 7GeV
e− 4GeV
Asymmetric B- factory
magnetic separation.

Fig.11.



The general lay-out of the VLEPP facility:
1-initial injector; 2-intermediate accelerator; 3-debuncher-monochromatizer; 4-storage ring; 5-buncher; 6-accelerating sections; 7-RF-generators; 8-pulse deflector; 9-focusing lenses; 10-collision points; 11-spectrometer; 12-helical ondulator; 13-the beam of γ-quanta; 14-conversion target; 15-residual electron (positron) beam; 16-electron (positron) beam experiments; 17-the second stage.

Fig. 12.