Review of Φ-Factories

Mario Serio, Gaetano Vignola, DAΦNE Project Team [1]
INFN, Laboratori Nazionali di Frascati (LNF) - 00044 Frascati (Roma) - Italy

Abstract

The main accelerator physics and technology issues of electron-positron Φ-Factories are discussed. Advantages and drawbacks of possible colliding schemes are reviewed. The most relevant technological issues at DAΦNE, now under construction at LNF, are discussed.

1. INTRODUCTION

1.1 Energy frontiers vs. Luminosity frontiers.

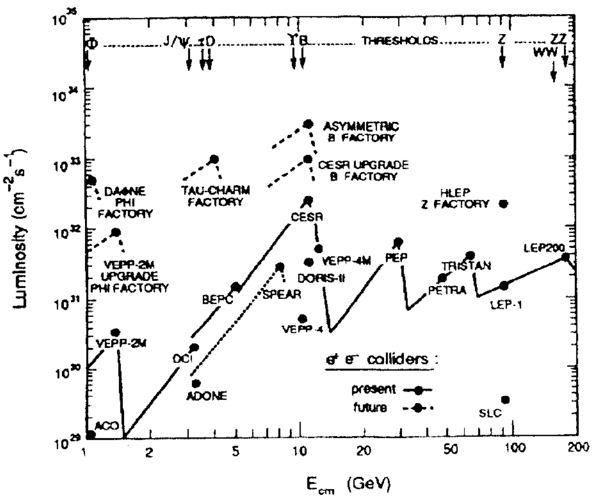

Figure 1 - Luminosity of present and future e^+e^- colliders and factories in the range 1÷200 GeV (from Ref. [2]).

In the last years, besides the continuing interest of physicists towards physics at colliders with higher and higher energy, considerable interest has developed towards very high precision measurements and in particular to the study of CP violation on colliders optimized and running at specific $s\bar{s}$ or $b\bar{b}$ resonances such as Φ, ϒ, etc. The prerequisite to the realization of these colliders is abundant production of Φ or ϒ particles reliably around the clock, hence the name *factories*.

In contrast to colliders at the energy frontiers, where huge financial effort, large international collaborations and large laboratories set the typical scale, in the race to very high luminosity at relatively low energy, the typical scale can well be that of a medium size national/regional Laboratory (e.g., LNF) and the financial effort is in most cases affordable by a single Institution.

The composition and the numeric consistency of both the physics and accelerator groups is not such to pose serious sociological and logistic problems, as often is the case with large collaborations.

The exploitation of local facilities, skills and experiences certainly affect the approach, making the design somehow site-dependent; new ideas and considerable R&D are nevertheless solicited.

1.2 Physics at a Φ-Factory

The realization of factories at the Φ energy (~1 GeV c.m.) has been proposed at several laboratories. The main motivation for a Φ-Factory is that it can provide a method to measure the ratio of the CP violating parameters ε'/ε with a precision of ~ 5 10^{-4} [3]. To fulfill the experimental requirements in order to verify CP violation, the yield of Φ particles necessary must be of the order of ~10^{10}/year. Then, given the peak cross section at the Φ resonance, $\sigma_{peak} = 4.4\times10^{-30}$ cm^2 and assuming 10^7 sec of operating time in one year, the average luminosity $<\mathcal{L}>$ must be ~2.3×10^{32} cm^{-2} sec^{-1}. To date, the maximum luminosity attained at the Φ energy is that of VEPP-2M, 4.3×10^{30} [4]. A luminosity improvement of about two orders of magnitude is then necessary.

2. LUMINOSITY STRATEGIES

Being the luminosity $\mathcal{L}$ the primary and most distinctive feature of a Φ-Factory, a brief digression is in order.

The luminosity per interaction point (IP) is, by definition:

$$\mathcal{L} = f\,\frac{N^+N^-}{\Sigma} = f\,\frac{N^+N^-}{4\pi\sigma_x\sigma_y}\ [\mathrm{cm^{-2}\,sec^{-1}}]\,, \qquad (1)$$

with f the crossing frequency, N_{+-} the number of particles in the positron and electron beam, Σ the superposition area and $\sigma_{x,y}$ the rms horizontal and vertical beam sizes at the IP, assuming gaussian shape and head-on collision.

We make some simplifying assumptions: beams are bunched and h different bunches per beam collide at the IP; the number of particles per bunch N and the horizontal and vertical beam sizes are equal in both beams. The collision frequency is $f = h\,f_{rev}$, with f_{rev} the revolution frequency.

The single bunch luminosity $\mathcal{L}_o$ is limited by the beam-beam interaction. When two bunched beams collide, one bunch feels a focusing effect from the other, whose strength is described by the so called beam-beam tune shift parameter ξ:

$$\xi_{x,y} = \frac{r_e\,N\,\beta_{x,y}}{2\pi\,\gamma\,\sigma_{x,y}\,(\sigma_x+\sigma_y)}\,, \qquad (2)$$

with r_e the classical electron radius, $\beta_{x,y}$ the betatron functions at the IP, and γ the particle energy in units of rest mass. There is experimental evidence of a limit on the maximum value that ξ can take, beyond which the beam-beam effect is so strong that instability and beam blow-up occur and the lifetime and the luminosity are substantially reduced.

We can express the luminosity as:

$$\mathcal{L} = h\mathcal{L}_o = h\,f_{rev}\,\frac{N\,\gamma\,\xi_y}{2r_e\,\beta_y}\,\left(1+\frac{\sigma_y}{\sigma_x}\right). \qquad (3)$$

Equal tune shift in both planes ($\xi = \xi_x = \xi_y$) is obtained when:

$$\text{Emittance ratio} = \kappa = \kappa_\beta = \frac{\beta_y}{\beta_x}\ \rightarrow\ \frac{\sigma_y}{\sigma_x} = \kappa\,.$$

Under this condition the luminosity can be written as:

$$\mathcal{L} = h\mathcal{L}_0 = h\, f_{rev}\, N \left(\frac{\gamma}{2r_e}\right) \frac{\xi}{\beta_y} \;(1+\kappa)\,. \qquad (4)$$

By inspection of the simple formula (4) we can identify the relevant parameters that could be pushed to limit to improve the luminosity. None is without limitation or drawbacks, however. Let's review them briefly.

2.1 Revolution frequency f_{rev}.

The size of the typical detector cannot be much smaller than 3÷5 m, imposing a limit on the ring circumference to no less than ~20 m, corresponding to a revolution frequency of ~15 MHz. Assuming a filling factor <~0.5 for the bending magnets, one readily arrives at very intense bending fields, and small bending radii, with strong non-linear components which tend to reduce the dynamic aperture.

In addition, a substantial fraction of the machine length must be dedicated to RF, injection, beam instrumentation etc., which adversely affect the longitudinal coupling impedance with a larger relative weight than in a longer machine. In small rings, coherent synchrotron radiation is the source of non negligible *vacuum* impedance.

2.2 Number of bunches h.

Increasing the number of bunches has the nasty side-effect of parasitic crossings outside the interaction region (IR), which contribute to the beam-beam tune shift parameter, but not to the useful luminosity. Parasitic crossings can be eliminated by means of electrostatic separators, but in this case, the maximum number of bunches is limited by the constraint of having at least one half betatron wavelength between two parasitic crossing points. It is possible to go around this problem by adopting a scheme with two separate rings, tangent at the IP(s). The problem of avoiding parasitic crossing is circumvented in this way, except for the common part of the two storage rings, where in any case the beams must be kept separated either by electrostatic separators, or by accepting to collide at small angle. In case of separated rings, it is a reasonable choice to make the ring size larger, with many bunches, keeping the number of particles per bunch relatively small. Multibunch instabilities, however, can pose a serious limit because of the high total current.

2.3 β-function at the IP

A very small value of β at the IP has strong impact on the whole ring lattice design. First of all, in order to leave sufficient material-free solid angle to the detector, the first quadrupoles cannot be too close to the IP. The betatron function grows parabolically, taking a very large value at the quadrupole. The chromaticity is strongly affected and a powerful sextupolar correction must be provided elsewhere in the ring, with a corresponding reduction of dynamic aperture.

Also important, due to the parabolic increase of β around the IP, the transverse size increases along the bunch length and to keep the advantage of having small dimensions at the IP, the bunch length σ_l must be shorter or at most of the same order of β, otherwise geometric reduction of the luminosity occurs, the so called hour-glass effect. To achieve short bunch length puts an heavy burden on the RF system and on the machine impedance budget. Malignant instabilities can arise because of the very high peak current.

2.4 Coupling κ

In spite of the theoretical factor of two increase in luminosity that one can get with round beams κ~1, this solution is seldom used.

To exploit full coupling requires the two β functions at the IP to be of the same order, with strong focusing in both planes: the chromaticity is increased and the sextupolar correction is more complicated and makes the ring lattice less flexible. Moreover, there is an additional difficulty in the design of the interaction region, where space is at a premium. This is the reason why practically all existing colliders adopt the flat beam scheme, with strong focusing only on the vertical plane. An alternative way to achieve equal (small) values at the IP is by means of strong solenoidal focusing.

2.5 Tune shift parameter ξ

A substantial luminosity increase can also be obtained by increasing ξ. Unfortunately, it seems not possible to achieve arbitrarily large values of ξ without incurring in serious limitations. Besides the physical mechanism of the ξ limitation, which is very involved and far from having been solved theoretically in a conclusive way, there is an experimental experience over most existing and past colliders that the maximum ξ achievable is much like an universal constant. Namely, averaging over most electron colliders: $\xi \sim 0.04 \pm 0.015$.

According to theoretical arguments and simulations [5,6], there could be a net gain in the maximum ξ by adopting the round beam scheme, although there is not general consensus on this conclusion [7].

We cannot overestimate the relevance of experimental data on this very crucial issue. At the time of writing, the only one experiment made at CESR [8] has not dramatically confirmed the goodness of the round beam approach, even though, for various reasons, the experimental conditions were not very favorable and this datum has not to be considered conclusive in any way.

There is a very interesting plan of making round beams at VEPP2M [9] with a solenoidal focusing scheme similar to that proposed for the INP Φ-Factory [10]. In this way the possibility of increasing the beam-beam limit with round beams will be tested and hopefully validated in a realistic context.

Of course, all the above parameters are not free, affecting each other in several respects and confronting with other possible limitations of the storage ring design.

Not less important than the maximum luminosity is the luminosity lifetime. In addition to the peak luminosity, which is a qualifying figure, also the time between successive fills of the ring(s) is very important for a "practical" experiment to take data.

3. OVERVIEW OF Φ-FACTORIES

In this section we review the proposals and projects for Φ-Factories in the world. The main parameters relevant to the luminosity are summarized in Table I.

3.1 UCLA

The UCLA Φ-Factory design [11] consists of a compact race-track storage ring of 17 m circumference, equipped with 6 superconducting dipoles of 4T with large good field region and no curvature for simplicity of realization and reduction of cost.

Table I - Summary of luminosity related parameters of Φ-Factories

	INP	UCLA *	DAΦNE	KEK
Design Luminosity $\mathcal{L}$ (cm^{-2} sec^{-1}) ($\times 10^{32}$)	10	3. (10.)	1.3 ->5.	30.
Design Luminosity/bunch $\mathcal{L}_0$ ($\times 10^{32}$)	10	3. (10.)	0.043	0.1
Total current lifetime (min)	11	45	230	15
Beam-Beam contribution to lifetime (min)	11	100	1500	600
Circumference (m)	35.2	17.4	97.7	120
Number of rings	1	1	2	2
Number of IRs	1	1	1 + (1)	1
Crossing type	Head-on	Head-on	H. angle	H. angle
Crossing half angle (mrad)	0	0	10÷15	20
Number of bunches per beam	1->3	1	30 ->120	300
Number of particles per bunch ($\times 10^{10}$)	20.	40. (16.)	9.	6
Momentum compaction factor α	.03 - .06	.11 (~0)	.005	.007
Horizontal β at IP (cm)	1.	19	450.	100.
Vertical β at IP (cm)	1.	3.9 (0.3)	4.5	1.
RMS Bunch length (mm)		30 (<3)	30	4.7
Energy loss (radiation) per turn (KeV)	32.1	14.1	9.3	14.5
Horizontal emittance (mm×mrad)	.47	3.2 (1)	1.	1.14
Coupling factor κ	1	0.2	0.01	0.01
Tune shift parameter ξ	>0.1	0.05	0.04	0.03

* Numbers in parenthesis refer to Phase 2 (QIR).

A sketch of the proposed layout is given in Fig. 2. One of the two straight sections is occupied by the RF cavity, the other one by a *small* detector. In the UCLA proposal an initial luminosity: $\mathcal{L} = 3\times10^{32}$ cm^{-2} sec^{-1} is achievable working with single bunches of 4×10^{11} particles, high emittance, κ = 0.2 and a rather conventional low-β interaction region. Due to the very compact design, special sextupoles are employed to correct the chromaticities.

At a second stage the lattice will be modified to obtain a "Quasi Isochronous Ring" (QIR) with a design luminosity $\mathcal{L} = 10^{33}$ cm^{-2} sec^{-1}. The idea is to shorten the bunch to the millimeter range by making the first order momentum compaction vanish, enabling very small values of the vertical betatron function at the IP, so that, even with a lower current (1.6×10^{11} particles), a higher luminosity can be obtained.

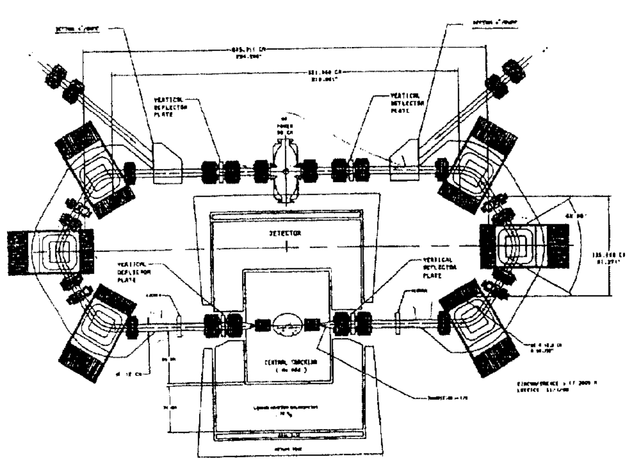

Figure 2 - Sketch of the UCLA Φ-Factory

3.2 INP

The Φ-Factory under construction at INP, Novosibirsk [10], undoubtedly incorporates the most innovative and exotic design ideas. It is 35 m long and has a rather peculiar "figure of eight" shape (see Fig. 3). One bunch per beam circulates in the machine and the collision points merge in the central part, allowing the bunches to cross at the same IP two times per revolution.

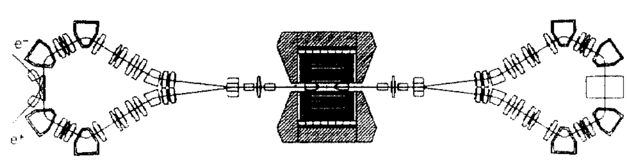

Figure 3 - Sketch of the INP Novosibirsk Φ-Factory

The number of particles/beam is 2×10^{11}, corresponding to an average current of ~ 270 mA/beam. An essential feature of the project is the strong solenoidal focusing: superconducting solenoidal magnets of 11 T, incorporated within the detector, are used to obtain equal low-β values of ~1 cm at the IP and, at the same time, to exchange the horizontal and vertical planes at each crossing, creating the same emittance in the two planes. The bending magnets are also superconductive at 6.5 T.

The first-stage luminosity design is 10^{33} cm^{-2} sec^{-1} in the single bunch mode. This ultra high luminosity can be reached exploiting the round beam option, with the operating point on the main coupling resonance with no degeneration of the normal modes of oscillation. The design is based on the idea that round beams can get a value of ξ_{max} higher than 0.1 in both planes.

A second stage is foreseen, with up to three bunches and electrostatic separation at unwanted IPs. The luminosity at this stage will improve by a factor 3+10.

The lifetime is of the order of few minutes and therefore injection at 0.1+0.2 Hz is planned.

The project is supported by the Russian Government within the State Program on High Energy Physics, but the financing plan has been drastically detained and INP has to support the project within its own budget.

3.3 DAΦNE and KEK

The INFN-LNF project DAΦNE [12] and the KEK [13] proposal are similar. They both exploit existing buildings and facilities and use the same approach of storing many bunches (≤120 and ≤ 300, respectively) in two separate rings ~100 m long. The beams are very flat and are brought to collision at a horizontal angle.

The approach is based on conventional techniques, normal conducting (NC) dipole magnets, high field NC wigglers and room temperature RF cavities.

In the KEK project the two rings are superposed, with two long straight sections (SS), one for the IR, the other for the RF, and two short sections, one for injection and the other for the feedbacks.

DAΦNE adopts a different solution in that the rings lay in the same plane and are asymmetric with a short and a long half. Two IRs can be accommodated. The crossing angle can be changed by powering a small dipole, located after the splitter magnet that separates the trajectories of the two beams.

The short SS is used for the RF and the feedback systems, the long one for injection.

In both projects the lattice is a modified Chasman-Green. The wigglers, accommodated in dispersive regions in the arcs, are used to increase the radiation and to control the emittance.

4. STATUS OF DAΦNE

DAΦNE has been approved and funded in 1990; the detailed engineering design started in 1991 and the construction is proceeding steadily. A general description of the facility has been given in [12]. The beginning of the commissioning is scheduled by 1996.

The initial effort is concentrated to ensure the accumulation of at least 30 + 30 bunches for an initial routine luminosity $\mathcal{L} = 1.3\ 10^{32}\ cm^{-2}\ sec^{-1}$.

In the following sections we give the status of the principal systems.

Detailed information on the various subsystems are found in other papers presented at this Conference.

4.1 Injector

A powerful, reliable and stable injection system has been recognized as a very important requisite to get the target average luminosity, because of the rather high number of positrons and electrons to store (up to 10^{13} in ~5 min) and of the necessity of frequent injections.

The injector complex consists of an e^+/e^- Linac, an Accumulator/damping ring and transfer lines. All the components of the injection chain can operate at full energy and top-up injection is foreseen, to keep the average luminosity high.

The Linac can deliver e^+/e^- beams at 50 Hz. It is now under test at Titan-Beta [14] and the installation at LNF will begin by the end of 1994.

The 32.56 meter long Accumulator/damping ring is used to accumulate at 50 pps the required number of electrons (positrons) in one RF bucket and to damp the transverse and longitudinal emittance of the Linac beam.

The damped beam is extracted at ~1 Hz and injected into a single bucket in the main ring. This solution avoids saturation of injection and the aperture requirements for injection in the main rings are relaxed.

Magnetic channels transfer the beams from the Linac to the Accumulator and from the Accumulator into the main rings, snaking inside the already existing tunnels and buildings around Adone, now dismantled (see Fig. 4).

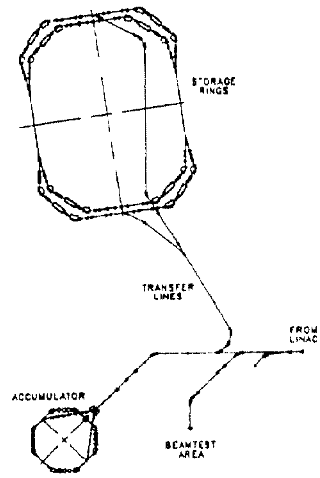

Figure 4 - Layout of DAΦNE and injector

The Accumulator and transfer lines are now under construction by Oxford Instuments and Ansaldo respectively, and the commissioning will start in 1995.

4.2 Emittance Wiggler

Four NC 1.8 T, 2 meters long, 40 mm gap, wiggler magnets are present in each ring, to increase the radiated energy. In addition, by slightly changing the optical functions in the wigglers, it is possible to tune the beam emittance over a wide range without deteriorating the damping time.

A wiggler prototype built by Danfysik (Denmark) has been delivered to LNF, and after a complete set of measurements, the authorization has been released for series production, with some modification suggested by the tests.

The magnetic quality of the wiggler meets the requirements of the DAΦNE Main Rings. Numerical simulations confirm that perturbation introduced by integrated sextupolar term in the wigglers is not harmful.

4.3 Vacuum System

The total pumping speed installed on each storage ring is a huge 125000 l/s over 100 meters of vacuum chamber. The main ring vacuum system is dimensioned for an operating pressure of 1 nTorr with ~ 5 Amp of circulating current. It is also required to have a rapid recovery of operating pressure after an intervention in the vacuum chamber or after an accident.

The vacuum system is based on Ti sublimation pumps (TSP) located in the vacuum antechamber of the arc sections, right close to copper absorbers. In addition, sputter ion pumps are used to pump down CH_4 and noble gasses.

Different surface finishing and treatments on two Al 5083 prototypes of the arc vacuum chamber have been investigated. Using the obtained results, which confirmed our choices, the cleaning procedures and the operational procedure for the flashing of Ti filaments in the TSPs have been assessed.

Detailed specifications for the arc vacuum chamber are completed and the contract for the fabrication awarded.

4.4 RF

The first main ring cavity is now under construction. Because of the large current and large number of bunches, the reduction of the beam-cavity spectra interaction is the most demanding feature of the DAΦNE RF system.

The RF cavity design aimed at significantly reduce the impedance of the high order cavity modes (HOM) by a proper shape of the resonator and, more effectively, by coupling off the HOM electromagnetic fields with waveguides.

The waveguide, whose cutoff frequency is higher than that of the accelerating mode, are connected to the cavity surface and terminated to 50 Ω on the other side, by means of broadband (0.5÷3 GHz) waveguide to coaxial transitions under vacuum, which have been developed at LNF [15] to this purpose. This solution avoids the use of RF lossy materials within the waveguides, in the ultra high vacuum of the accelerator.

This system has been tested on a cold prototype and the measured HOM Qs are below those required to damp multibunch instabilities with our bunch-by-bunch feedback system.

The RF power source at 368.25 MHz is a 150 kW/CW TH2145 klystron amplifier developed by Thomson Tube Electronique and successfully factory tested at full power. The estimated beam power is ~100 kW at the full design current.

4.5 Interaction Region

One of the two IRs will accommodate the detector KLOE [3], designed mainly to study CP in neutral K decays. The other one is assigned to a smaller detector FINUDA [16], designed to study hypernuclei formation and decay. The KLOE construction is in a more advanced status.

The KLOE interaction region is 10 m long. The low-β quadrupole triplets, of permanent type, are 46 cm far from the IP and are confined in a cone of 9° half aperture, leaving a material-free solid angle for the apparatus of ~ 99%. The first 2 quadrupoles of the triplets have already been built by Aster Enterprises and the measured field quality exceed our specifications. It is a requirement of the experiment to have a large (radius ~ 10 cm) aperture vacuum chamber at the IP as transparent as possible to the produced particles. The outer parts of the IR vacuum chamber are made of stainless steel with a copper coating inside to reduce the ohmic losses.

The inner section, bulb-shaped at the IP, is made of 0.5 mm thick pure beryllium, directly brazed onto the stainless steel pipe. Inside the spherical part of the chamber a 50 micron beryllium shield provides a continuous profile to the vacuum chamber to reduce RF losses. Water pipes, brazed as close as possible to the interaction point, provide the cooling needed to compensate for the thermal load on the vacuum chamber.

The supporting system consists of two independent structures: the detector support and the triplet assembly support, to allow relative freedom of mechanical alignment of the permanent magnet quadrupoles without affecting the detector. The detector supporting structure holds also the vacuum chamber.

The pumping system is a combination of lumped sputter ion pumps, distributed sputter ion pumps and non evaporable getter pumps. There are no pumps inside the detector near the IP.

The pumping system is able to reach a mean pressure of about $5 \cdot 10^{-10}$ Torr at full beam current after 2 or 3 months of conditioning.

5. REFERENCES

[1] The DAΦNE Project Team: S. Bartalucci, M. Bassetti, M.E. Biagini, C. Biscari, R. Boni, A. Cattoni, V. Chimenti, A. Clozza, S. De Simone, G. Di Pirro, A. Drago, A. Gallo, A. Ghigo, S. Guiducci, H. Hsieh, Q. Huamin, F. Marcellini, C. Marchetti, M.R. Masullo, M. Migliorati, C. Milardi, M. Modena, L. Palumbo, L. Pellegrino, M.A. Preger, G. Raffone, C. Sanelli, F. Sannibale, M. Serio, F. Sgamma, B. Spataro, A. Stecchi, L. Trasatti, C. Vaccarezza, M. Verola, M. Vescovi, S. Vescovi, G. Vignola, J. Wang, Y. Xianming, H. Yu, M. Zobov.

[2] J. Kirkby in "Frontiers of Particle Beams: Factories with e^+/e^- Rings" - Lecture Notes in Physics 425, Springer-Verlag, M. Dienes et al (Eds.), p. 381 (1992)

[3] The KLOE Collaboration, "KLOE, a general purpose detector for DAΦNE", Frascati Internal Note LNF-92/019 (IR), April 1992.

[4] P.M. Ivanov et al., "Luminosity and beam-beam effects on the electron positron storage ring VEPP-2M", in Proceedings of 3rd advanced ICFA beam dynamics workshop Novosibirsk 1989 - Ed. I. Koop and G. Tumaikin.

[5] S. Krishnagopal, R. H. Siemann, "Simulation of Round Beams", in Proceedings of 1989 IEEE Particle Accelerator Conference, Chicago 1989, p.836 (1989).

[6] N. S. Dikansky et al., "Incoherent Beam-Beam Effects for Round Beams in the Novosibisrsk Phi-Factory Project", in Proceedings of 1991 IEEE Particle Accelerator Conference, San Frascisco 1991, p.523 (1991).

[7] K. Hirata (CERN-KEK), "Round and Flat Beams in the Phi-factory", LNF Note Ares-15, 12/10/1989 (1989).

[8] P. Bagley et al, "Nearly Equal β* at CESR, Proceedings of 1991 IEEE Particle Accelerator Conference, San Frascisco 1991, p.467 (1991).

[9] A.N. Filippov et al., "Proposal of the Round Beam Lattice for VEPP-2M Collider", Proceedings of XVth International Conference on High Energy Accelerators, Hamburg1991, p. 1145 (1992).

[10] L. M. Barkov et al, "Status of the Novosibirsk Phi-Factory Project", in Proceedings of 1991 IEEE Particle Accelerator Conference, San Frascisco 1991, p.183 (1991).

[11] C. Pellegrini, The UCLA Φ-Factory Project, Proceedings of Workshop on Physics and Detectors for DAΦNE - Frascati, April 9-12 1991, p.83.

[12] DAΦNE Project Team, "DAΦNE Status Report", Proc. of 3rd EPAC Conference - Berlin, 1992.

[13] K. Hirata and K. Ohmi, "Feasibility of a Φ-Factory in KEK", 1991 Particle Accelerator Conference, San Francisco 1991, p. 2847 (1991).

[14] K. Whittam et al., "Design of the e+/e- Frascati Linear Accelerator for DAΦNE', in 1993 Particle Accelerator Conference, Washington D.C., USA, May 1993, pp. 611-613.

[15] R. Boni et al., "A Broadband Waveguide to Coaxial Transition for HOM Damping in Particle Accelerator RF Cavities", LNF 93/075(P), 1993 (to be published on Particle Accelerators).

[16] The FINUDA Collaboration, "FINUDA, a detector for nuclear physics at DAΦNE", Frascati Int. Note LNF-93/021 (IR), May 1993.