Lecture given at the joint US-CERN School on Particle Accelerators
"Frontiers of Particle Beams, Factories with e^+e^- Rings",
Benalmadena, Spain, 29 Oct - 4 Nov, 1992.

Φ-Factory Design

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Introduction

The search for fundamental interaction laws stimulates continuously the accelerator community to push up the energy of accelerators. Recently the interest for high accuracy measurements in already explored energy regions put forward the requirement for a new generation of colliders, the e^+ e^- factories, working at the energies of hadronic resonances and producing a very high rate of events with a luminosity increased by at least two orders of magnitude with respect to the present values. Such high luminosity poses interesting new problems to both the detector and accelerator physicists.

The lowest energy factory is expected to work at the Φ resonance (~ 1 GeV) and is mainly dedicated to the investigation of CP violation. The construction of a collider in Φ energy range requires a relatively small investment, in terms of budget and man power, and can therefore be afforded by medium size laboratories. A strong advantage for this kind of project is the small size of the groups which allows the participation to all problems concerning the detector and the accelerator.

The basic requirements of a Φ-Factory are:

- *Luminosity* = $10^{32} \div 10^{33}$ cm^{-2} sec^{-1} at the c.m. energy of 1.02 GeV. This is a challenging request: the maximum luminosity in this energy range has been obtained by VEPP-2M[1] and is two orders of magnitude lower ($L \sim 5\ 10^{30}$ cm^{-2} sec^{-1}). The maximum luminosity ever obtained is of the same order but has been obtained at an energy one order of magnitude larger ($L \sim 1.8\ 10^{32}$ cm^{-2}sec^{-1} at the energy of 5.3 GeV in CESR[2]).
- *High average luminosity*. The peak cross-section at the Φ resonance is:

$$\sigma_{peak} = 4.4\ 10^{-30}\ \mathrm{cm}^2$$

The Φ production required for the precision experiments on CP violation is at least 10^{10} events per year, which corresponds to L = 2.3 10^{32} cm^{-2} sec^{-1} with 10^7 seconds in a year; to obtain such a high average luminosity a very reliable storage ring is needed.

- *Large free solid angle* in the detector: the dream of the experimentalists is a storage ring with a high luminosity and no machine components near the luminosity source, which of course are conflicting requirements. Coordinated designs of detector and accelerator are necessary.

Most of experimental proposals ask for symmetric energies: two beams colliding at 510 MeV, with equal parameters (beam current, emittance, dimensions, energy spread). The possibility of using Linac against ring will not be treated in this lesson. A general overview will be given on the Φ-Factory design strategy, on the main new items and on the existing projects.

1 Basic design parameters

The single bunch luminosity for an electron-positron storage ring collider is given by the well known formula:

$$L = f \frac{N^2}{4\pi \sigma_x \sigma_y} \tag{1}$$

where f is the collision frequency, N is the number of electrons and positrons per bunch (assumed to be the same) and σ_x and σ_y are the horizontal and vertical rms beam sizes at the interaction point (IP).

The luminosity is limited by the beam-beam interaction. When two beams collide, one sees the other as a focusing lens, whose strength is given by a dimensionless parameter, the so called beam-beam tune shift

$$\xi_x = \frac{r_e N \beta_x}{2\pi \gamma \sigma_x (\sigma_x+\sigma_y)} \qquad \xi_y = \frac{r_e N \beta_y}{2\pi \gamma \sigma_y (\sigma_x+\sigma_y)} \tag{2}$$

r_e being the classical electron radius, $\beta_{x,y}$ the betatron functions at the IP, and γ the particle energy in units of its rest mass. The value of ξ has an empirical limit that will be discussed later. In order to maximize the luminosity L it is convenient to have the beam-beam tune shifts maximum and equal in the two planes; this is possible if the ratio between the emittances, the coupling factor κ, is equal to the ratio of the beam rms sizes at the IP. It follows that κ is also equal to the ratio of the betatron functions at the IP:

$$\kappa = \frac{\varepsilon_x}{\varepsilon_y} = \frac{\sigma_x}{\sigma_y} = \frac{\beta_x}{\beta_y} \tag{3}$$

With $\varepsilon = \varepsilon_x + \varepsilon_y$, the beam-beam tune shift can be rewritten as:

$$\xi = \frac{r_e}{2\pi\gamma}\frac{N}{\varepsilon} \tag{4}$$

By introducing ξ in the luminosity expression, we set:

$$L = \pi f \frac{\gamma^2}{r_e^2}\frac{\xi^2 \varepsilon\ (1+\kappa)}{\beta_y} = \pi f \frac{\gamma^2}{r_e^2}\frac{\xi^2 \varepsilon\ (1+\kappa)}{\kappa\ \beta_x} \tag{5}$$

This formula shows the relevant accelerator parameters to play with in order to maximize the luminosity; a discussion on each of them follows to illustrate the choices that can be made.

1.1 Linear tune shift parameter ξ

When two beams collide the electromagnetic interaction between particles acts as a focusing lens producing a tune shift. The interaction force is linear only up to an extent of about one rms beam size and has its maximum at 1.6 σ (see Fig. 1). The beam-beam tune shift linear part, given by (2), is proportional to the beam density (strength of the interaction), to the betatron function β (sensitivity to interaction) and inversely to γ (rigidity of the beam). The focusing strength on a particle and therefore its tune shift depend on the particle position inside the bunch: due to beam-beam interaction a tune spread arises whose width is well represented by ξ, because the maximum tune shift corresponds to particles which are inside the core of the bunch distribution and therefore see the linear part of the interaction force.

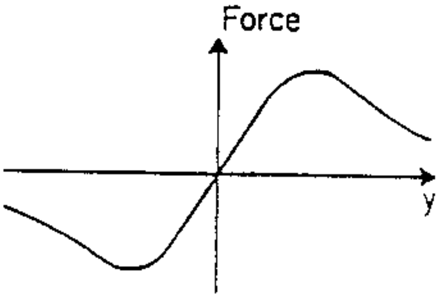

Fig. 1 - Beam-beam force

It is clear from (5) that a luminosity increase can be obtained by increasing ξ. Unfortunately it seems not possible to go to high values of ξ: the beam-beam tune shift increases linearly with the beam current up to a maximum value. Further increase of the beam current results in beam blow-up or even in beam loss. Experimental evidence shows that the ξ limit is:

$$\xi = 0.038 \pm 0.013$$

averaged over most existing colliders. This number seems in principle not dependent on the energy, nor on the age of the accelerators.

Fits of the experimental data have been performed by several authors, e.g. Seeman in 1985[3] and more recently by Bassetti[4], analizing the best performances of a group of e^+-e^- colliders. It is not easy to find a general law from the collider measurements, because not all the machines were optimized to the same extension, and their performance can be limited by different problems, like single bunch current threshold, rf, alignment, beam separations, etc. Seeman concluded with a possible dependence of ξ_y on the energy E, on the characteristic ring bending radius ρ and on the number of crossings per turn N_i:

$$\xi_y \propto \frac{E}{\sqrt{N_i\,\rho}}$$

Last news from CESR[2] say that with the removal of one of the two IPs the luminosity and the value of ξ_y have fortunately almost doubled, which seems in disagreement with the above fit, even if one has to consider that some ring characteristics were changed between the two configurations: different beam separation schemes, different solenoid compensation, elimination of dispersion at the IP.

Bassetti has considered a larger number of colliders including old and low energy accelerators, and new and high energy ones like LEP, and found that the best fit for ξ_y is the following:

$$\xi_y \propto \frac{1}{\left(\rho \sqrt{N_i}\right)^{.4}} \left(E \sqrt{\frac{\beta_x}{\varepsilon_x}}\right)^{.5} \kappa^{-1.7}$$

It is interesting to note that the fit does not depend on the energy E, because even if E appears in the formula, being ε_x proportional to E^2, the E dependence cancels out. The fit favours flat beams against round.

Anyway, when designing a new factory, a more or less conservative value for ξ must be assumed, so fixing N/ε.

ξ may change with the tune in a not easily predictable way: the ring lattice should therefore be widely flexible, in order to compensate for unexpected effects in the beam-beam interaction.

1.2 Low beta

From the luminosity formula it is evident that the smaller β at the IP the higher the luminosity: the beam-beam interaction changes the divergence of particles; where the divergence is large the unwanted deflection is less troublesome. Anyway β cannot be squeezed at will, first of all because of the geometrical limitation of luminosity[3]. The betatron function, starting from a symmetry point, shows a parabolic dependence on the distance s:

$$\beta_y(s) = \beta_y^* \left(1 + \left(\frac{s}{\beta_y^*} \right)^2 \right)$$

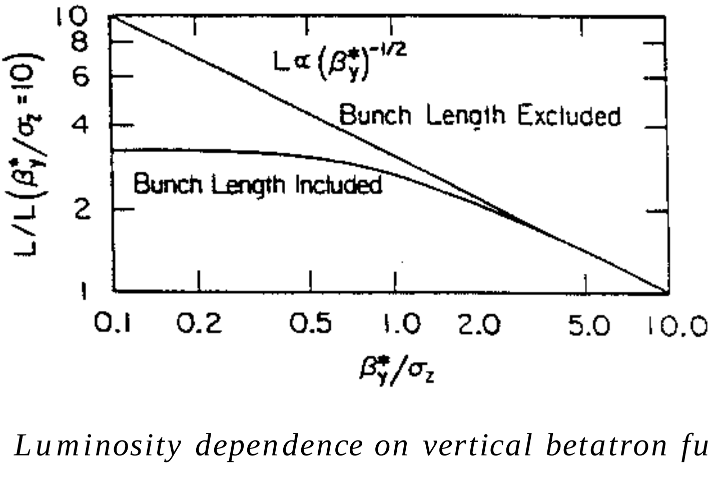

Fig. 2 - Luminosity dependence on vertical betatron function[3].

The betatron function within the bunch increases rapidly, so that to keep the advantage of having a low beta, β_y^* must be larger than the half bunch length σ_z which is determined by the ring rf system, impedances and single bunch instability thresholds.

Moreover low β_y^* implies high chromaticity with a corresponding reduction of dynamic aperture and also strong focusing near the IP, where normally there is lack of free space because of detector requirements.

Reasonable values for both σ_z and β_{oy} are in the order of few centimeters.

1.3 Emittance

The equilibrium emittance is determined by the radiation process which depends mostly on the characteristic radius of the bending field, and on the properties of the lattice.

To increase the luminosity one would like to have large emittance, but ε cannot be made arbitrarily large because of the machine physical aperture necessary for a reasonable beam lifetime.

The dynamic aperture is also sensitive to ε: large emittance means that most particles perform betatron oscillations in the magnetic field region where multipole components are more dangerous.

Furthermore, being $\xi \propto N/\varepsilon$, increasing ε means increasing the bunch current, to which beam instabilities are related.

The relatively large value of the emittance (~ 1 mm mrad) can be obtained either with small bending radius dipoles or with wigglers which allow also emittance tuning.

1.4 Coupling factor κ

The coupling factor can be chosen between 0 and 1, corresponding respectively to a very flat or to a round beam.

$\kappa = 1$ implies *round beam* at the IP: $\beta_x = \beta_y$, $\varepsilon_x = \varepsilon_y$, $\sigma_x = \sigma_y$

For the Φ-Factory, due to the relatively low energy of the beam, it is possible, at least in principle, to focus a round beam to the low beta values with a solenoidal field, while in higher energy rings quadrupoles are necessary to obtain strong focusing and it is critical to focus in both planes at the same point in the lattice.

With $\kappa = 1$ a factor 2 is directly gained on the luminosity (see formula 5). Some beam-beam simulations claim that a higher ξ can be obtained[5,6] but this has not yet been tested. There exists a very interesting proposal of making round beams in VEPP-2M[7], to check the physics of beam-beam interaction in this configuration.

Strong focusing in both planes tends to increase the maximum value of the betatron functions near the IP. As a consequence, the chromaticity grows up and the aperture requirements become more demanding in the horizontal plane. Also the vertical aperture becomes critical due to the vertical emittance, with the obvious drawback on vacuum and complexity of element designs.

A low value of κ implies a *flat beam*, with a vertical emittance much smaller than the horizontal. Such a choice is convenient from the point of view of apertures and chromaticity, because only one of the planes is critical.

It implies also reduction of ion trapping, which is very important in multibunch operation.

Accurate orbit correction to ensure the design coupling is necessary.

1.5 Collision frequency

There are two basic strategies to increase the collision frequency: to store the beams in two rings in multibunch operation and intersect at one or maximum two IPs, or alternatively to use very compact rings and only one bunch per beam.

The compact ring design maximum collision frequency is few tens of MHz and therefore the single bunch luminosity:

$$L_o = L / n_b$$

where n_b is the number of bunches in each beam, must be pushed well beyond the limit of existing machines, while in double ring multibunch operation the value of L_o is of the order of that achieved in operating machines and it is the number of bunches that must be increased.

Both choices have their advantages and drawbacks, which will be discussed later.

2 Projects and proposal

There are different projects around the world for Φ-factories; two of them (Novosibirsk and UCLA) follow the compact ring approach. The other three are two rings configurations. In the following table their main parameters are listed, together with those of VEPP-2M for comparison.

A general description of compact ring characteristics and some words on each proposal follow. The same for the two rings configuration with special emphasis, of course, on the Frascati project.

Table 1 - Main parameters of Φ-factory projects.

	Nov[5] *Russia*	UCLA[8] *USA*	DAΦNE[9] *Italy*	KEK[10] *Japan*	Mainz[6] *Germany*	VEPP2M[1] *Russia*	
C (m)		35	17	98	120	29	18
β_y^* (cm)		1.0	3.9(.3)*	4.5	1.0	0.12	4.5
σ_Z (cm)		~1	3(.3)	3	.5	1	
ε_x(mm mrad)		.47	3.2(1)	1.0	1.1	.22	.46
κ	1	0.2	0.01	0.01	1	0.01	
N (10^{10})		20	40	9	6	8	3.7
I_{tot} (A)		.5	1.2(.5)	5	7	.8	.1
n_b	1	1	120	300	6	1	
f (MHz)		17	17	368	750	62	17
θ (mrad)		0	0	12.5	20	0	0
ξ_x	.10	.05	.04	.03	.08	.05	
ξ_y	.10	.05	.04	.03	.08	.02	
α	.03 -.06	.11(~0.)	.005	.007	.018		
τ (min)		< 5	40	300	15	60*	
$L_o(10^{32})$		10	2 (10)	0.04	0.1	1.6	0.07
L (10^{32})		10	2 (10)	5	30	10	0.07

* Numbers in parenthesis correspond to QIR

** Only τ_{bb}

3 Compact ring

The size of a Φ detector is of the order of 3 to 5 m; to fit it inside a ring a minimum circumference of ~ 20 m is needed, corresponding to a maximum collision frequency of the order of 15 MHz. This relatively low value of f implies that to obtain the desired luminosity one or more of the following parameters must be pushed to *critical values:* low beta; emittance; bunch density; beam-beam tune shift.

The small bending radius can be obtained with superconducting dipoles, whose *high nonlinearities* can limit the dynamic aperture, already critical due to the large emittance.

The large *synchrotron radiation power density* on the vacuum chamber walls must be faced with special design of the vacuum chamber (for example the antichamber at the UCLA ring).

A fundamental problem of the compact ring is the high rate of particle loss due to single beam-beam bremsstrahlung which shortens the lifetime to few minutes. Continuous filling of the ring is necessary.

3.1 Novosibirsk Φ-Factory

The Novosibirsk proposal is a very innovative idea. The ring is a bone-shaped machine (see Fig. 3) where the two beams, in the single bunch mode, circulate in opposite directions and cross at one point thanks to the introduction of negative curvature sections in the arcs.

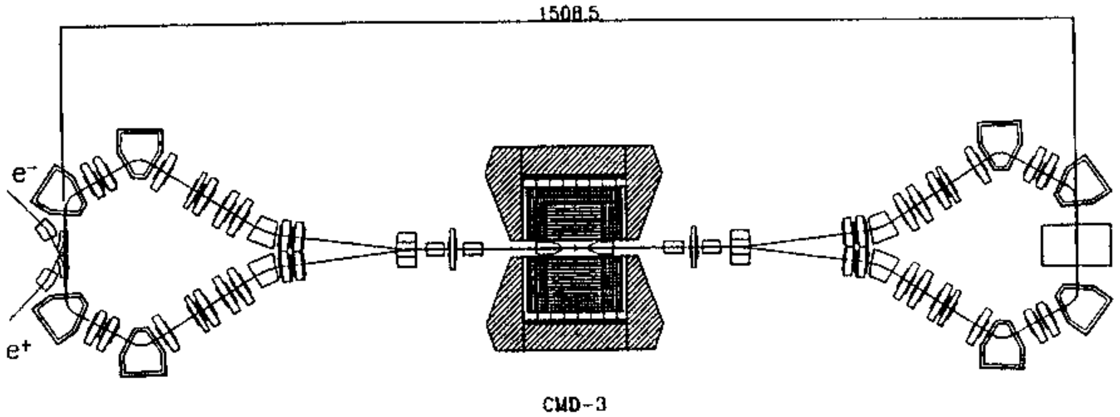

Fig. 3 - Novosibirsk Φ-Factory Layout.

Round beams are used: a sc solenoid (11 T) around the IP rotates the transverse planes by $\pi/2$: the betatron oscillation normal modes are vertical in one arc and horizontal in the other so that the emittances in the two planes are the same. Beams are focused to very small beta values in both planes by the same solenoid.

A very high value of ξ (> 0.1) is claimed to be obtainable.

The working point is placed on the main coupling resonance $\nu_x - \nu_y = 0$. The tunes are shifted along the coupling resonance and do not trespass on the 2-dimensional coupling sidebands.

SC dipoles (6.5 T) are used to obtain the small bending radius.

The beam lifetime of few minutes is considered satisfactory and manageable with the injection chain, consisting of a full energy linac and a positron cooling ring.

A later stage with 3 bunches per beam is envisaged, applying electrostatic beam separation at the IP sides to reach luminosities higher than 10^{33} cm^{-2} sec^{-1}.

3.2 UCLA Φ - Factory

The UCLA Φ-Factory design consists of a small machine of ~ 20 m circumference, equipped with SC dipoles. A sketch of the proposed layout is given in Fig. 4.

Three successive phases are envisaged, with increasing luminosity.

The Compact Superconducting Ring (SMC) with L = 2 10^{32} cm^{-2} sec^{-1} working in single bunch mode, with low coupling (κ = 0.2) and high emittance.

The Quasi Isochronous Ring (QIR) with 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 @ IP, so that, even with a lower current with respect to the phase I, a higher luminosity can be achieved.

The Linac against Ring option, finally, should lead to a luminosity larger than 10^{33} cm^{-2} sec^{-1}.

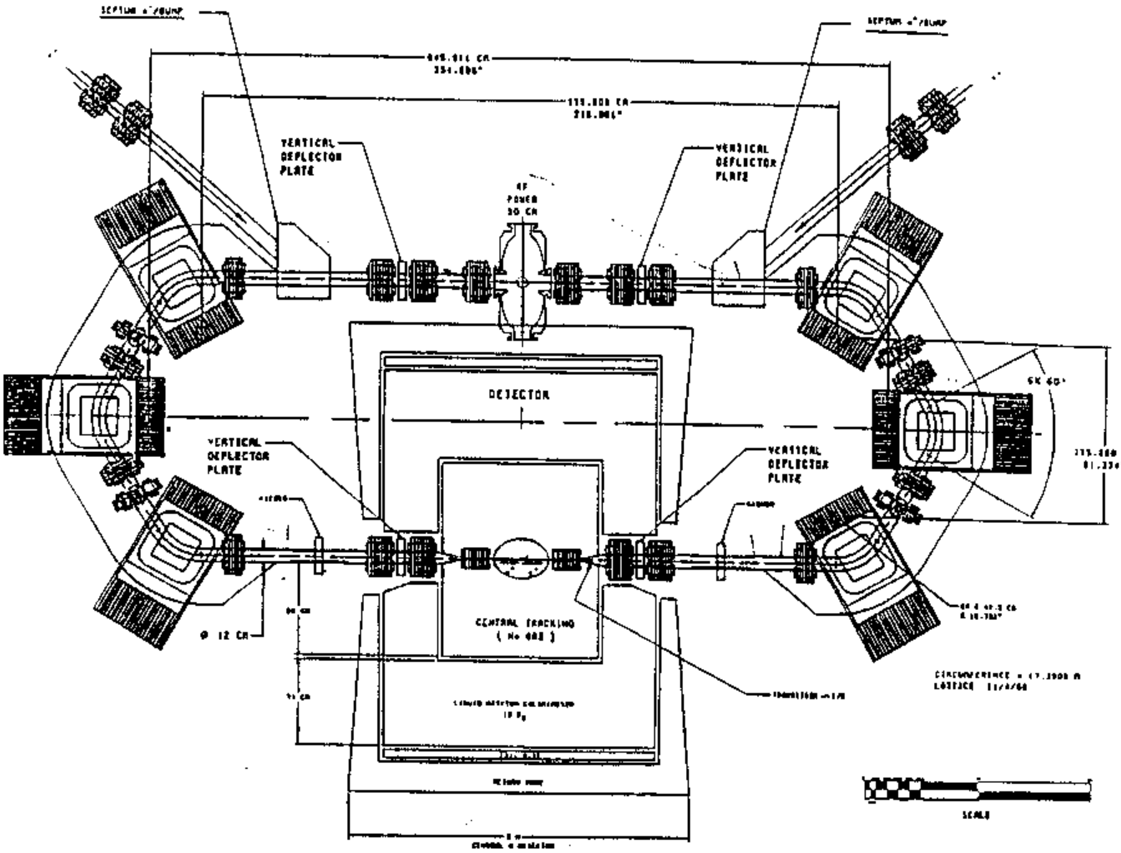

Fig. 4 - UCLA Φ-Factory layout.

4 Double ring-multibunch operation

The choice of increasing the collision frequency by storing many bunches in two rings leads to a design based on conventional technology, as far as the lattice is concerned.

The short distance between bunches obliges the beams to cross at an angle in order to suppress parasitic crossings.

The key problem are multibunch instabilities which must be faced with feedback systems specially designed, rf cavity design with HOM suppression and low impedance in all vacuum chamber components.

The discussion of the main characteristics of this kind of project will follow the DAΦNE criteria design. The KEK project will be shortly described later, as it follows more or less the same criteria.

4.1 DAΦNE - Frascati

DAΦNE, the Frascati Φ-Factory, is up to date the only funded project for factories in the world.

It consist of two rings, of about 100 m circumference, intersecting at an angle in the horizontal plane in two points, to be fitted in the old ADONE hall. It will accommodate two experiments, KLOE and FI.NU.DA., the first one specially designed for the CP-violation investigation, the second one studying nuclear physics. A layout of the rings is shown in Fig. 5. The ring is not symmetric with respect to the two IPs: looking at the figure it is clear that because of the crossing angle the arcs joining the two IPs are of different lengths.

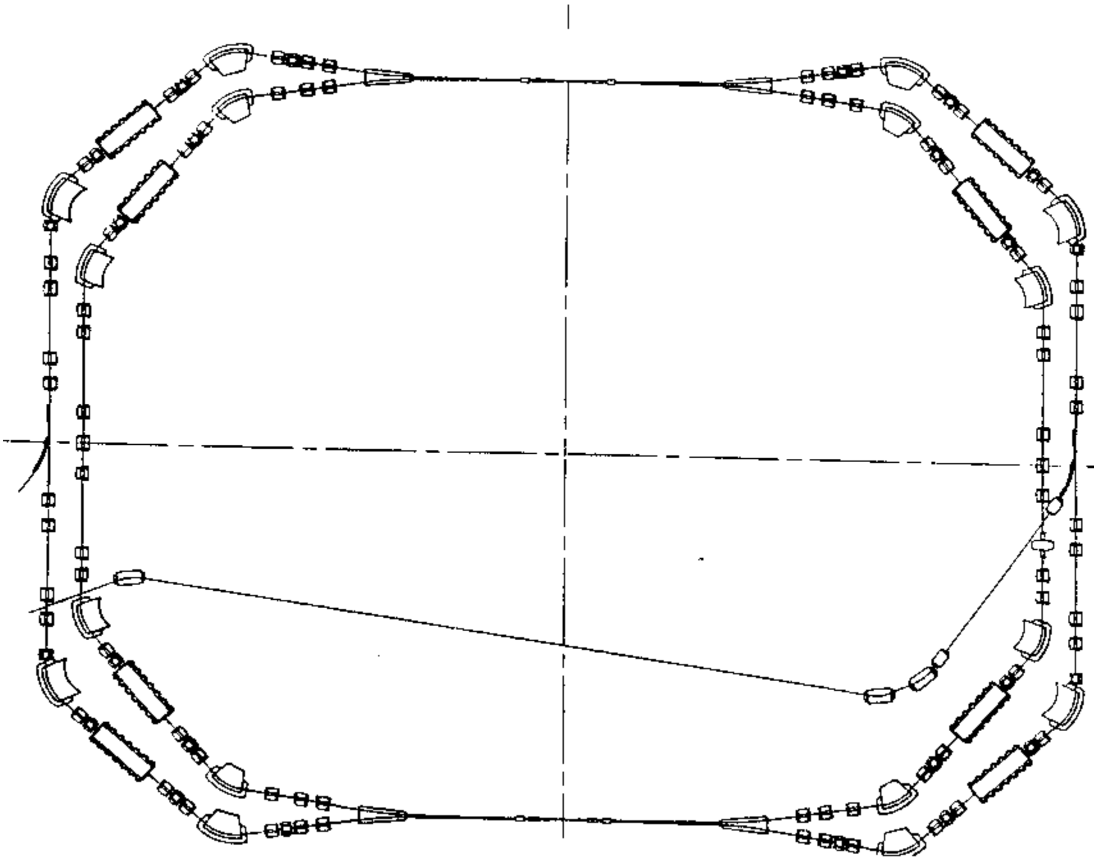

Fig. 5 - DAΦNE layout

Flat beams (κ = 0.01), multibunch operation and crossing angle are the key feature of the project. The emittance is controlled by means of four wigglers in each ring, located in the dispersive zone.

Being the two experiment detectors equipped with strong solenoids (0.6 T x 2.1 m @KLOE and 1.5 T x 2 m @ FI.NU.DA), the perturbation of the machine optics obliges a coordinated design of the interaction region and the detector.

The interaction regions in between the two splitting magnets which separate the two beam trajectories, are shared by the two rings. The magnetic axis of their elements is the bisectrice of the nominal closed orbits of the two rings. The two interaction regions are equivalent from the optics point of view, i.e. with the same first order transfer matrix, so that the optical functions and the beam separation are the same at the Interaction Region ends. This solution simplifies injection, tuning and chromaticity correction in the different modes of operation.

In the Interaction Regions the transverse coupling due to the detector solenoid is corrected by two compensating solenoids at the detector ends whose total field integral is opposite to the detector one. In both experiments all or some of the low beta quadrupoles are immersed in the solenoidal field. To eliminate the coupling effect quadrupoles should be rotated following the angle given by:

$$\theta_{sol} = \int \frac{B_z\, dz}{2B\rho}$$

This continuos rotation is not feasible with a real quadrupole, so each quadrupole will be rotated by the average value of θ_{sol} along its length. To eliminate the residual coupling four parameters are needed, and the rotation angle of the three quadrupoles plus the field of the compensator solenoid can be used to block-diagonalize the transfer matrix from the IP to the split magnet.

4.1.1 Crossing angle

In multibunch configuration the reduced bunch to bunch distance forbids head-on collisions and beams must cross with an angle. Crossing can be in the horizontal or in the vertical plane. When beams collide with an angle synchro-betatron coupling arises: this has been proved in Doris[11] and by beam-beam simulations[12]. This effect can be avoided with a *crab* *crossing* scheme. The original idea was given by R. Palmer[13] for linear colliders and it has been later applied to ring colliders[14]. The principle is the following: a transverse deflecting rf cavity, located $\pi/2$ in β-phase advance from the IP and with the zero-crossing of the electrical field synchronous with the bunch center, gives to a particle an angular kick proportional to its distance from the bunch center. This kick transforms into a transverse displacement at the IP, thereby making the two bunches tilt and collide head-on. Another cavity, π away from the first, restores the original bunch orientation. This geometry allows a bunch spacing closer than a normal head-on collision, and consequently a higher collision frequency.

The required cavity voltage, assuming that the rms bunch length σ_z is small compared to $\lambda_{rf}/4$, where λ_{rf} is the rf wavelength of the cavity, is:

$$V_{rf} = \frac{E}{4\pi e}\frac{\theta\lambda_{rf}}{\sqrt{\beta^* \beta_c}}$$

being θ half the crossing angle, β^* the betatron function at the IP, β_c at the cavity location, both in the crossing plane.

This scheme requires rf phase φ and amplitude stability:

$$\Delta\varphi << \frac{4\pi\sigma}{\theta\lambda_{rf}} \qquad \frac{\Delta V_{rf}}{V_{rf}} << \frac{1}{\sqrt{N_\beta}}\frac{\sigma}{\sigma_z}$$

being σ the rms bunch size at the IP in the crossing plane and N_β the number of turns in a betatron damping time. With a flat beam, since β_x is much larger than β_y, the cavity amplitude V_{rf} is much lower and the tolerances much larger for the crossing in the horizontal plane. In fact tolerances are so large that for DAΦNE characteristic parameters a cavity is not necessary.

The key parameter describing the effect of the crossing angle on beam dynamics is what is called the *badness factor* a:

$$a = \theta\frac{\sigma_L}{\sigma_x}$$

It is a measure of the coupling between the radial and the longitudinal phase spaces generated by the crossing angle. This coupling, experimentally observed in DORIS I[11], limits the maximum achievable tune shift and, consequently the luminosity.

The simplest hypothesis one can make on the relation between a and ξ is:

$$\xi a = \text{const}$$

Suggestions on this value come both from observations at DORIS I and computer simulations. At DORIS I the maximum value of the tune shift ever obtained and the value of a were:

$$\xi = 0.01 \quad , \quad a = 0.5$$

In DAΦNE $a \sim 14\,\theta$, so that an angle of ~ 10 mrad seems safe from this point of view. Simulations[15] of particle tracking including beam-beam interaction with crossing angle confirm that no synchro-betatron dangerous coupling occurs up to an angle of ~ 100 mrad.

The effect of *parasitic crossings* must also be considered: when two beams collide at an angle 2θ the first parasitic crossing (p.c.) occurs at distance $l/2$ (l is the spacing between bunches) from the IP, being the bunches centers at a distance given by $d = l\,\theta$.

The tune shift due to the parasitic crossing is:

$$\xi_x = \frac{r_o\, N\beta_x}{2\pi\,\gamma\, d^2} \qquad\qquad \xi_y = \frac{r_o\, N\beta_y}{2\pi\,\gamma\, d^2}$$

where β_x, β_y are the betatron functions at the p.c. From the consideration that one beam could act as a scraper for the opposite beam particles passing inside its core, a criteria had arised[16]: the full separation should be at least 7σ so that particles one wishes to keep in the beam stay out of the opposite beam center.

To check this criteria simulations have been done with DAΦNE parameters[17], using the approximation of weak-strong interactions.

Two different effects have shown:

- Blow-up in the vertical emittance for particles inside the core which affect the *luminosity* (σ_y increase).
- Long vertical tails for particles which passes near the core of the opposite bunch which can affect the *beam lifetime.*

Both the effects depend on the current, on the beam separation, and on the *betatron functions* at crossing, but we got no evidence of the scraper effect. In fact a particle passing inside the opposite beam gets a tune shift which affects its betatron motion, but not necessarily cuts it out, also because a particle which sees the other bunch at one turn will probably not pass inside it again in the successive turns during a betatron damping time.

With DAΦNE design parameters 7σ at the p.c. is a safe number, but for example with a higher current a separation of 7σ would affect beam lifetime.

4.1.2 Rf and feedback system

The rf system must face one of the most harmful problems in high current storage rings working in multibunch operation: the high order modes (HOMs) of the rf cavities induce coupling of the relative motion of the n_b bunches through the wake fields left behind in the cavity by the bunches themselves giving rise to multibunch instabilities. The instability growth rate must be kept below the radiation damping rate by a proper cavity design and an appropriate feedback system.

The rf voltage necessary to compensate the energy losses due to synchrotron radiation and to HOMs is not very high (<< 1 MV): room temperature cavities are used. The choice of the frequency is usually related to the availability of rf sources together with the bunch length requirements: 350, 500 MHz are the most commonly used.

A large amount of R & D (Frascati, SLAC)[18] is in progress to develop a rf cavity having the lowest possible interaction with the beam spectrum. The research is essentially dedicated to two items:

* Cavity shape optimization to reduce the number of "trapped" HOMs by means of long tapered tubes (R/Q is reduced by an order of magnitude). Fig. 6 shows a sketch of the cavity shape model proposed for DAΦNE.
* HOM damping by coupling the more dangerous parasitic modes with loops or with waveguides propagating at their frequencies.

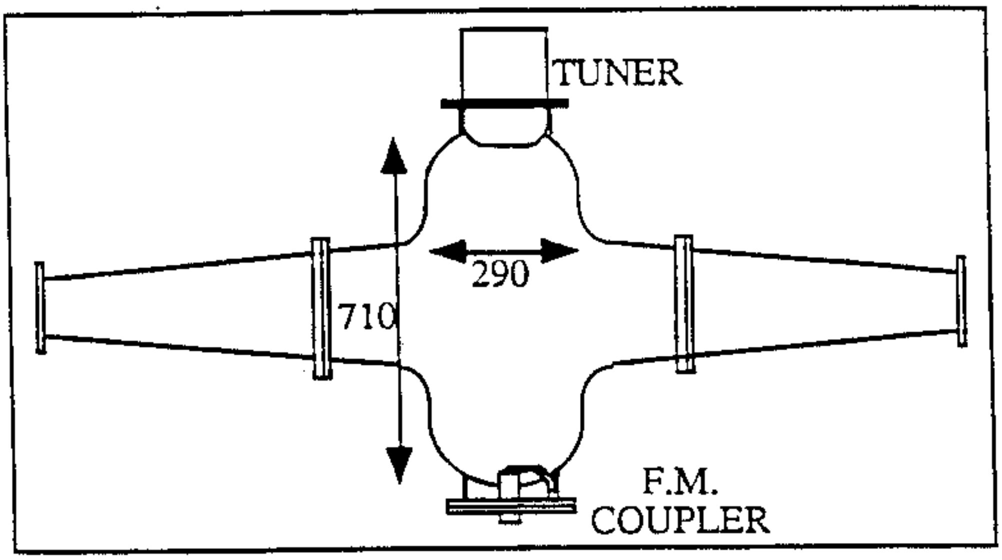

Fig. 6 - DAΦNE cavity shape.

Even with HOM damping or frequency shift the rise time of coupled bunch (cb) modes of oscillation can be much faster than the natural radiation and Landau damping time; moreover the probability for a damped HOM to cross a cb mode frequency is larger, due to the wider bandwidth. An all-mode feedback system (f.s.) capable to damp all the cb modes and the injection transients is then necessary.

In most operating rings the usual approach consists in detecting the bunch synchrotron phase error, rotating the signal in the longitudinal phase plane with a filter and finally amplifying and giving an energy kick with a kicker. This method requires a number of filters equal to the number of bunches, which of course becomes very demanding in multibunch operation.

On the contrary a bunch to bunch, time domain system[19] is now possible with the available electronic technology: in a mixed analog/digital f.s. the Digital Signal Processors (DSP) filters can implement several different channels, reducing the overall complexity. Moreover the digital system can be programmed in such a way as to maintain the correction signal just below the saturation limit of the power amplifier even in presence of large phase excursions. A modular approach allows to implement the system for a reduced number of bunches and to update it when a higher n_b is needed for the luminosity upgrade.

4.2 KEK Φ-Factory

The two beams are stored in two rings superposed and horizontally crossing with an angle. The lattice provides flat beams with high currents and large emittance.

The rf frequency is 1.5 GHz. Every two buckets are filled to avoid very large values of ε_x.

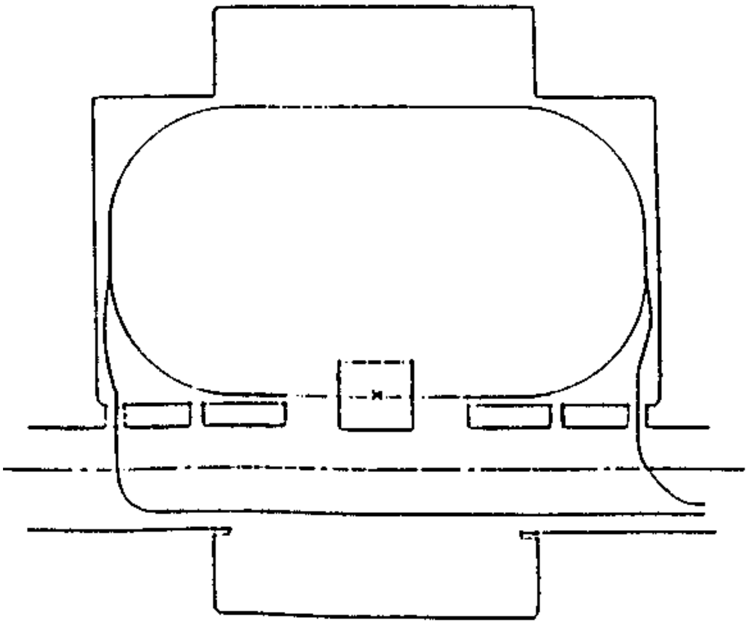

Fig 7 - KEK Φ -Factory layout.

4.3 Φ-Factory Design Studies at Mainz

Studies for designing a Φ-factory are being developed at Mainz. The proposal is a compromise between the compact ring and the double ring operation. The lattice consists of two rings intersecting at one point (see Fig. 8). Beams are round and following the Novosibirsk idea they are both focused and rotated by a superconducting solenoid; few bunches per beam ($n_b = 6$) give a collision frequency of 50 MHz. The short bunch length ($\sigma_z = 1$ cm) should be obtained with a special insertion made of dielectric material which should focus the beam longitudinally. A high design ξ value is proposed: $\xi = 0.08$, checked with beam-beam simulations.

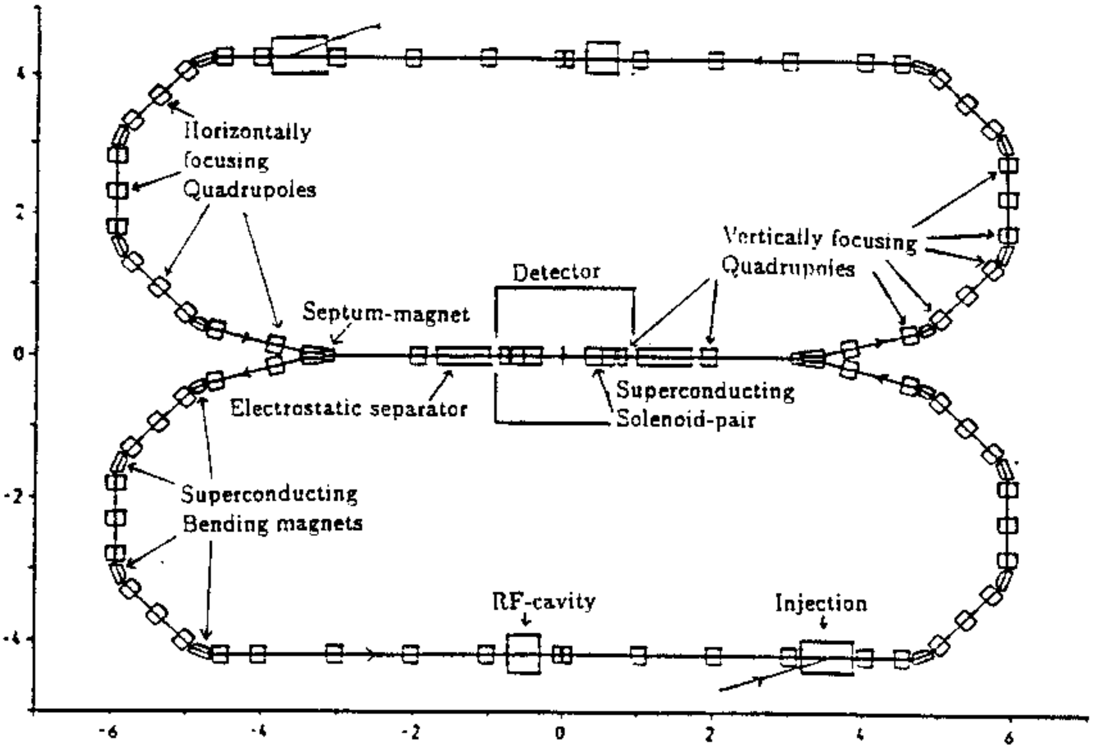

Fig. 8 - Mainz proposed Φ- factory layout.

5 Beam lifetime

Beam lifetime in an accelerator is a measure of how 'peaceful' the accelerator is: almost any single bunch instability and interaction between the beam and the surroundings reflects on the stability of the beam inside the vacuum chamber. A summary of the main considerations for beam lifetime follows.

a. *Apertures*

The bunch distributions follow gaussian shapes. The tails of the distribution get lost hitting the vacuum chamber or the dynamic aperture; the quantum beam lifetime τ is given by:

$$\tau = \frac{\tau_\beta}{2\, r_\beta}\, e^{r_\beta} \qquad r_\beta = \frac{1}{2}\left(\frac{A}{\sigma}\right)^2$$

τ_β being the betatron damping time and A the aperture. For typical values of τ_β (tens of milliseconds) $A = 6\ \sigma$ gives a lifetime of several hours, while $5\ \sigma$ reduces the lifetime to few minutes. Small rings with round beams and high emittances are of course critical from this point of view.

b. *Single bunch effects*

- Touschek effect: when scattered particles inside the bunch get a longitudinal momentum variation they can exceed the momentum acceptance of the ring, or if the scattering occurs in a dispersive zone the induced horizontal oscillation can exceed the transverse acceptance of the ring. This effect is very strong for low energy rings, especially for very flat beams because of its dependence on the bunch density and is in fact the main limitation for multibunch operation rings working with flat beams.
- Multiple Touschek effect: scattering between particles inside the bunch transfers momentum between the planes to which can be associated an increase in the transverse emittance which could exceed the transverse acceptance, either physical or dynamic. In Φ-factories this effect is not of much concern because the emittance is already large and its increment is only of few percent, well contained in the ring acceptance.

c. *Beam-gas interaction*

The scattering between beam particles and residual gas molecules can be elastic, producing betatron oscillations that can exceed the transverse acceptance, or inelastic (bremsstrahlung), producing energy oscillations exceeding the longitudinal acceptance.

Depends on vacuum and apertures: it is more demanding in small rings because of the higher synchrotron radiation pressure.

d. *Beam-beam bremsstrahlung*

The beam-beam decay rate is proportional to $L/(n_b\ N)$. In single bunch modes and at high luminosity the beam lifetime is reduced to few minutes.

6 Injection

The total number of positrons required to obtain the quoted luminosity is very high: $10^{11} \div 10^{12}$ for compact rings and ~ 10^{13} for double rings. Furthermore reliable operation asks for a short injection time, typically few minutes for the double ring configuration, 1 minute for the compact ring, to store the full current of both beams. It is clearly convenient to inject at full energy.

An accumulator, at the same energy of the main ring, is usually proposed to accumulate at lower f_{rf} to accept LINAC pulse. It is used also to damp the e^+ emittance and energy spread to values acceptable by the main ring system and to equalize the two beam characteristics.

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