LATTICE AND INTERACTION REGION DESIGN FOR TAU-CHARM FACTORIES

John M. Jowett

Abstract

A Tau-Charm Factory ($\tau c F$) is a high luminosity e^+e^- circular collider working in the energy range of the J/ψ resonance and τ -lepton production threshold.

The design of the optics for these colliders is particularly demanding since they require a variation of their emittances by about an order of magnitude between their initial high-luminosity phase and a future "monochromatic" phase in which the spread of collision energies is considerably reduced for CP-violation studies at the J/ψ resonance.

This lecture provides an introduction to τ -Charm Factory design with emphasis on beam optics and surveys several proposals to be found in the current literature.

Most designs are based on a double-ring scheme with vertical separation near the interaction point. The interaction region design must therefore deal with the vertical dispersion, either by matching it to zero or, in the monochromatic case, by arranging for a large enough value at the interaction point. The variation of emittances can be achieved by varying the phase advances in a FODO lattice or by tuning arcs constructed from achromatic modules. Extensive use of wigglers provides additional factors in emittance.

*Lecture given at the Joint US/CERN School on Particle Accelerators,
Benalmadena, Spain, 29 October to 4 November 1992*

Geneva, Switzerland

27 April 1993

1 Introduction

A Tau-Charm Factory (τcF) is a high luminosity e^+e^- circular collider working in the energy range of the J/ψ resonance and τ -lepton production threshold. A τcF would continue mining the rich seam of physics opened up by SPEAR at SLAC (Stanford) and further explored by BEPC (Beijing). Since the first proposal in 1987 [1, 2], a number of designs for such a collider have been produced. As the requirements of the physics community have evolved, these designs have become more complex and now make essential use of some of the most interesting concepts proposed in the 30-year history of e^+e^- storage rings. While some of these were first mooted many years ago, a τcF is almost certainly going to be the first opportunity to put them into practice. Ideas such as monochromatization and longitudinal polarization were previously somewhat compromised by being conceived as modifications of existing storage rings. From the point of view of an accelerator physicist, a τcF presents not only a particularly demanding challenge in the performance required but also an exciting opportunity to work these elegant, yet untried, ideas into the design from the outset.

In the past, frontier e^+e^- colliders have, on the whole, been designed to meet the same goals, essentially those of the highest possible luminosity and low background at their chosen energies. Colliders from 1 to 200 GeV centre-of-mass energies are broadly similar in design (if the appropriate scaling is applied). In the “factory era” this has changed. The experimental conditions required of ϕ -, τ -c- and B-factories are so specialised and diverse that the machine designs differ much more than one might expect, given that their centre-of-mass energies span just one order of magnitude.

This lecture discusses the principles of τ -Charm Factory design, referring to several examples to be found in the literature, rather than laying down a single path to the ideal τcF . Each of these has something to teach us. A final design, incorporating all the best features in the happiest synthesis, is yet to be made and certainly requires further preliminary research on certain aspects: we can do no more than take a snapshot of a rapidly developing field. The list of references is intended as a starting point for further study. The emphasis here is on optics, particularly the less familiar aspects. Other critical aspects such as collective instabilities, the beam-beam effect, vacuum, the RF system, feedback and other hardware topics are treated by other lecturers.

2 Requirements For τcF Physics

Among present proponents of a τcF , one can distinguish a broad consensus, driven by the needs of specific measurements and moderated by realism, on what the performance goals should be. The machine would have a two- or three-phase programme as follows.

Initial high luminosity phase The first designs of a τcF aimed to provide an extremely high luminosity with maximum reliability and flexibility. The collider should work at centre-of-mass energies in the range

$$w = \sqrt{s} = 2E_0 = 3\text{--}5 \text{ GeV} \quad (1)$$

and attain its highest luminosity

$$L \simeq 1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1} \quad (2)$$

at $\sqrt{s} = 4 \text{ GeV}$, a little above the τ -pair production threshold. As we shall see below, meeting this objective with as conventional a design as possible leads to a design for a high emittance, high current, multi-bunch collider. Comparing with the $L = 8.2 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1}$ which is the best so far realised by BEPC [3], shows that even this first stage of the τcF is ambitious.

Monochromatic phase At the energy of the J/ψ resonance

$$\sqrt{s} = 3.097 \text{ GeV} \quad (3)$$

or $E = 1.548 \text{ GeV}$, some 10^{10} J/ψ decays/year are needed for CP-violation studies in the decays of $\Lambda^0 \bar{\Lambda}^0$ and $\Xi \bar{\Xi}$ pairs [4]. However, the full width $\Gamma(J/\psi) = 0.086 \text{ MeV}$ is very narrow. With a typical collider's centre-of-mass energy resolution, $\sigma_e = \langle (E - E_0)^2 / E_0^2 \rangle \simeq 10^{-3}$ only a small fraction of the collisions would occur with centre-of-mass energy within $\Gamma(J/\psi)$. One would need a luminosity of

$$L = 5 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1} \quad (4)$$

to create enough J/ψ s. Otherwise the only way is to reduce the energy spread in collision by means of a “monochromatic” collision scheme (a special insertion design which has never been tested). We shall see that this requires a low-emittance optics.

Ultimate phase Monochromatization of collisions would be even better if combined with longitudinally polarized beams, another long-standing idea which has never been realised at any e^+e^- collider. A polarization scheme which does not use the usual Sokolov-Ternov radiative mechanism to polarize the beams was recently proposed [5] for a τ -Charm Factory.

We shall see that the requirements of these different phases pull the parameters of the machine in different directions: from high to low emittance. It is obvious that they cannot all be met by a single configuration. Present thinking is that we should try to design a machine which can be *adapted* relatively easily. Ideas for achieving the necessary flexibility within the same basic structure have been proposed recently by several authors [5, 6, 7, 8, 9]. Within a given configuration, further flexibility in the accessible range of parameters is achieved by means of various wiggler magnets.

For as long as no-one implements a monochromator scheme, doubts can always be cast on the feasibility of the second phase. Studies would be done during the operation of the first phase which must, for the sake of safety, produce a substantial output of physics. It will do so if it attains luminosities of a few times $10^{32} \text{ cm}^{-2}\text{s}^{-1}$ which must, therefore, be the primary initial goal of the project.

3 Basic Parameter Choices

The design of a collider starts with the dynamics of the collision process itself (essentially the beam-beam effect). Working outwards from the interaction point (IP) this determines the size, shape and intensity of the beams which in turn determine the focusing structure, size and other gross features of the storage ring (or rings).

In this section we shall relate the luminosity to the phase-space distribution of the beam in order to see how to choose the parameters which determine this distribution. The formulation will be rather more general than usual since we want to cover cases (such as monochromator schemes) with non-vanishing dispersion at the IP. Although the treatment is meant to be as self-contained as possible, some basic notions from the statistical mechanics of electron storage rings [10, 11] will be found helpful.

3.1 Beam Distribution

In a discussion of luminosity, it is convenient to work with the basic set of phase space coordinates of particles in each beam denoted by $\mathbf{X} = (x, p_x, y, p_y, z, \varepsilon)$ where x and y are the radial and vertical *total displacements* from the closed orbit, $\varepsilon = (E - E_0)/E_0$ is the energy deviation and p_x , p_y and z are appropriate conjugate variables.

Note that these are *not the normal modes* of linearised motion around the closed orbit. In a further stage of the analysis, it is customary to split the transverse displacements into components due to betatron and synchrotron motion by introducing the *dispersion functions*, $D_x(s)$ and $D_y(s)$ so that

$$x = x_\beta + D_x \varepsilon, \quad y = y_\beta + D_y \varepsilon. \quad (5)$$

This canonical transformation decouples the energy and transverse oscillations up to quadratic terms in the Hamiltonian. In almost all cases of interest, it is further arranged that the betatron coupling effects (terms $\propto x_\beta y_\beta$) are weak and that two of the true normal modes coincide with x_β and y_β at the IP. Then it can be shown [11] that the equilibrium between radiation damping and quantum excitation results in gaussian phase space distributions of particles *at the IPs*:

$$f^\pm(\mathbf{X}) = \frac{\tilde{f}^\pm(p_x, p_y, z)}{\sqrt{8\pi^3 \beta_x^* \varepsilon_{xc} \beta_y^* \varepsilon_{yc} \sigma_\varepsilon^2}} \exp \left\{ -\frac{(x - D_x^* \varepsilon)^2}{2\beta_x^* \varepsilon_{xc}} - \frac{(y - D_y^* \varepsilon)^2}{2\beta_y^* \varepsilon_{yc}} - \frac{\varepsilon^2}{2\sigma_\varepsilon^2} \right\}. \quad (6)$$

Quantities referring to the IP are “starred” and positron and electron bunches are distinguished with superscripts $+$ or $-$. Apart from noting that $\tilde{f}^\pm$, like $f^\pm$ itself, is normalised to unity, the details of $\tilde{f}^\pm$ are of no concern here. The distribution is characterised by just three parameters: ε_{xc} and ε_{yc} are the natural emittances, determined by the magnetic lattice of the ring(s) and some weak ($\kappa \ll 1$) betatron coupling, and σ_ε is the fractional energy spread as we shall see below.

The gaussian distribution (6) is generally valid over most of the beam in the limit of low beam intensities. The “tails” of the distribution at large amplitudes may be altered by non-linear single-particle effects. At high intensities, both the core and the tails may be modified, e.g., by the beam-beam interaction [12, 13]. Even then, however, one can often approximate the distribution by (6) provided different values of ε_{xc} and ε_{yc} are used to account for “beam-beam blow-up”. We shall implicitly do so several times in the following sections; it should be clear which formulae depend on this assumption; the advantage of the gaussian distribution is that all averages discussed below can be calculated analytically using some straightforward, if tedious, transformations.

3.2 Beam Sizes and Correlation Functions

For any function $\mathcal{A}(\mathbf{X}^+, \mathbf{X}^-)$ (possibly depending on variables of particles from both bunches), let us define averages over the distribution functions of the bunches at the IPs as

$$\langle \mathcal{A} \rangle^\pm = \int f^\pm(\mathbf{X}^\pm) \mathcal{A}(\mathbf{X}^+, \mathbf{X}^-) d\mathbf{X}^\pm, \quad \langle \mathcal{A} \rangle^* = \langle \langle \mathcal{A} \rangle^+ \rangle^- . \quad (7)$$

Then we can evaluate the beam sizes as, e.g.,

$$\sigma_x^* = \sqrt{\langle x^2 \rangle^\pm} = \sqrt{\beta_x^* \epsilon_{xc} + D_x^{*2} \sigma_\epsilon^2}, \quad (8)$$

$$\sigma_y^{*2} = \sqrt{\langle y^2 \rangle^\pm} = \sqrt{\beta_y^* \epsilon_{yc} + D_y^{*2} \sigma_\epsilon^2} = \sqrt{\beta_y^* \kappa^2 \epsilon_{xc} + D_y^{*2} \sigma_\epsilon^2} = \kappa \sigma_x^* \sqrt{\beta_y^* / \beta_x^*}. \quad (9)$$

The fractional energy spread is

$$\langle \epsilon^2 \rangle^\pm = \sigma_\epsilon^2. \quad (10)$$

It is also easy to calculate *correlation functions* between position and energy such as deviation

$$\langle x\epsilon \rangle^\pm = D_x^{*\pm} \sigma_\epsilon^2, \quad \langle y\epsilon \rangle^\pm = D_y^{*\pm} \sigma_\epsilon^2. \quad (11)$$

This shows the dispersion functions in a new light. Rather than thinking of them as “derivatives of the closed orbit with respect to momentum”, i.e., as related to shifts of the centre of the beam distribution with RF frequency, we can also consider them as normalised correlation functions of position and energy *within* the beam distribution.

3.3 Luminosity and Differential Luminosity

In terms of the numbers of particles in each bunch, $N^\pm$, the number of bunches, k_b , and the revolution frequency f_0 , the general formula for *luminosity* is

$$L = k_b f_0 N^+ N^- \langle \delta(x^+ - x^-) \delta(y^+ - y^-) \rangle^*. \quad (12)$$

The Dirac delta-functions express the fact that luminosity is related to *collisions* in an intuitively appealing way. If we assume that the beams pass through each other head-on, only the transverse coordinates enter in (12). When a positron with energy deviation ϵ^+ collides with an electron of energy deviation ϵ^- , the centre-of-mass energy is

$$w = \hat{w}(\epsilon^+, \epsilon^-) \stackrel{\text{def}}{=} 2E_0 \sqrt{1 + \epsilon^+} \sqrt{1 + \epsilon^-} \simeq E_0(2 + \epsilon^+ + \epsilon^-) \quad (13)$$

and the *differential luminosity* [14, 15, 16] or luminosity per unit centre-of-mass energy is:

$$\Lambda(w) = k_b f_0 N^+ N^- \langle \delta(x^+ - x^-) \delta(y^+ - y^-) \delta(w - \hat{w}(\epsilon^+, \epsilon^-)) \rangle^*. \quad (14)$$

Clearly,

$$L = \int_0^\infty \Lambda(w) dw. \quad (15)$$

In the special case of the distribution (6), w also has a gaussian distribution about the mean $2E_0$ with standard deviation

$$\sigma_w^2 = L^{-1} \int_0^\infty w^2 \Lambda(w) dw - 4E_0^2. \quad (16)$$

Figure 1: Principle of a monochromator scheme: positrons with higher-than-average energy tend to meet electrons with lower-than-average energy and vice-versa. Positrons with energy $E_0(1+\epsilon)$ will, on average, have the vertical position $y = D_y^*/\epsilon$ for the collision optics specified in (20).

3.3.1 STANDARD HIGH LUMINOSITY OPTICS

The first phase of the τ cF will use a conventional flat-beam collision optics with no dispersion at the IPs:

$$D_{x\pm}^* = D_{y\pm}^* = 0. \quad (17)$$

There is therefore *no correlation* between position and energy in the colliding bunches (the functions in (11) vanish). Evaluating the luminosity using (6) we get the familiar result

$$L = L_0 = \frac{k_b f_0 N^+ N^-}{4\pi \sigma_x^* \sigma_y^*}, \quad (18)$$

where $\sigma_x^* = \sqrt{\beta_x^* \epsilon_{xc}}$, $\sigma_y^* = \sqrt{\beta_y^* \epsilon_{yc}}$.

The differential luminosity is simply

$$\Lambda(w) = \Lambda_0(w) = \frac{L_0}{\sqrt{2\pi} \sigma_w} \exp \left\{ \frac{-(w - 2E_0)^2}{2\sigma_w^2} \right\}, \quad \sigma_w = \sqrt{2} \sigma_e E_0 \quad (19)$$

where the root-mean-square (RMS) spread in centre-of-mass energies σ_w is typically $\simeq 1$ MeV.

3.3.2 MONOCHROMATOR OPTICS

The second phase of the τ cF will use a monochromator optics [14] whose purpose is to focus the luminosity onto a narrower region of particle spectrum than given by (19). This is achieved by means of *opposite correlations* between (vertical) position and energy in the beam distribution as indicated in Figure 1. According to (11) such correlations require opposite vertical dispersions for the two beams.

To illustrate the difference between equal and inverted dispersions, let us assume that there is in addition some horizontal dispersion D_x^* (possibly due to errors) which has the same sign for the two beams:

$$D_{x+}^* = +D_{x-}^* = D_x^*, \quad D_{y+}^* = -D_{y-}^* = D_y^*. \quad (20)$$

Other parameters being equal, the total luminosity is then reduced by the dispersions

$$L = \frac{L_0}{\sqrt{1 + \frac{D_x^{*2} \sigma_\epsilon^2}{\sigma_x^{*2}}} \sqrt{1 + \frac{D_y^{*2} \sigma_\epsilon^2}{\sigma_y^{*2}}}. \quad (21)$$

The differential luminosity is

$$\Lambda(w) = \frac{\Lambda_0(2E_0)}{\sqrt{1 + \frac{D_x^{*2} \sigma_\epsilon^2}{\sigma_x^{*2}}}} \exp \left\{ - \left(\frac{D_y^{*2}}{\sigma_y^{*2}} + \frac{1}{\sigma_\epsilon^2} \right) \frac{(w - 2E_0)^2}{2(\sqrt{2} E_0)^2} \right\}. \quad (22)$$

It is simpler to look at its value at the centre of the distribution

$$\Lambda(2E_0) = \frac{\Lambda_0(2E_0)}{\sqrt{1 + \frac{D_x^{*2} \sigma_\epsilon^2}{\sigma_x^{*2}}}}, \quad (23)$$

which is undesirably reduced by the D_x^* . On the other hand, the energy resolution is improved by D_y^*

$$\sigma_w = \frac{\sqrt{2} E_0 \sigma_\epsilon}{\sqrt{1 + \frac{D_y^{*2} \sigma_\epsilon^2}{\sigma_y^{*2}}}}, \quad (24)$$

i.e., σ_w has been reduced (in comparison to (19)) without reducing σ_ϵ . It is customary to define the “monochromatization factor” as the enhancement of energy resolution:

$$\lambda = \frac{\sqrt{2} \sigma_\epsilon E_0}{\sigma_w} = \sqrt{1 + \frac{D_y^{*2} \sigma_\epsilon^2}{\sigma_y^{*2}}}. \quad (25)$$

It is easy to show from (13) and (11) that $\langle wy \rangle^\pm = 0$: there is no correlation between w and the vertical position of the interaction vertex. The equal horizontal dispersion does correlate w with the position of the interaction vertex: $\langle wx \rangle^\pm = 2D_x^* \sigma_\epsilon^2$, a fact which may be of some use experimentally. From here on, however, we shall assume that the horizontal dispersion is designed to vanish, $D_x^* = 0$, in the monochromator optics. The total luminosity L is apparently reduced by the factor λ . Formally, from (19) and (23), we also have $\Lambda(2E_0) = \Lambda_0(2E_0)$.

For large values of $\lambda \gg 1$, as aimed for in present monochromator designs, the luminosity formula becomes

$$L \simeq \frac{k_b f_0 N^+ N_-}{4\pi \sigma_x^* D_y^* \sigma_\epsilon} = \frac{k_b f_0 N^+ N_-}{4\pi \sqrt{\beta_x^* \epsilon_{xc}} D_y^* \sigma_\epsilon} \quad (26)$$

implying that the experimental insertion design should aim for small β_x^* and larger β_y^* .

3.4 Luminosity at High Intensity

3.4.1 STANDARD HIGH LUMINOSITY OPTICS

If the emittances and beam sizes have their “natural” values, i.e., those calculated in the usual way [10, 11] from the radiation effects in the lattice, then luminosity formulae like (18) are valid only at sufficiently low intensity that there is no blow-up of the beam cores [12]. With the beam-beam effects thus “switched off”, we can re-write (18) as

$$L_0 = \frac{k_b I_b^2}{4\pi e^2 f_0 \sigma_x^* \sigma_y^*} = \frac{k_b I_b^2}{4\pi e^2 f_0 \epsilon_x \sqrt{\beta_x^* \beta_y^*}} \left(\kappa + \frac{1}{\kappa} \right), \quad (27)$$

where $I_b = eN_{\pm}f_0 = I/k_b$ is the current per bunch (now assumed to be the same for both beams).

The “unperturbed” vertical beam-beam tune-shift parameter (calculated on the basis of the “natural” σ s) is

$$\xi_{yo} = \frac{(I_b/e f_0) r_e \beta_y^*}{2\pi (E_0/m_e c^2) (\sigma_x^* + \sigma_y^*) \sigma_y^*} \quad (28)$$

with an analogous formula for ξ_{xo} . The formulae are simpler if we assume conventional flat beams and adjust the betatron coupling to the “optimal” value $\kappa^2 = \epsilon_{yc}/\epsilon_{xc} = \beta_y^*/\beta_x^*$ which maximises L_0 and makes $\xi_{yo} = \xi_{xo}$. (In practice it is better to try to minimise σ_y^* by all means available!)

To reach the beam-beam limit, corresponding to a specified ξ_{yo} and a given emittance ϵ_x , we need a bunch current

$$I_b = \frac{2\pi e f_0 (E_0/m_e c^2) \epsilon_x \xi_{yo}}{r_e} \quad (29)$$

and (27) becomes

$$L_0 = \frac{\pi k_b (1 + \kappa^2) f_0 (E_0/m_e c^2)^2}{r_e^2 \beta_y^*} \epsilon_x \xi_{yo}^2. \quad (30)$$

If I_b is limited (likely in the initial year or two of operation while single- or multi-bunch instabilities are being mastered), then (29) has to be re-written as an equation determining the emittance. Provided it is possible to stay at the beam-beam limit in such a case, $L_0 \propto I_b$, and it does not pay to have a large ϵ_x . For this reason it is important, even in the initial high-luminosity phase, to arrange for the emittance to be variable over a given range. The large values needed once design current is achieved should be accessible with the help of wigglers, starting from a lower value corresponding to the “bare” lattice. In LEP, for example, we now use a relatively low-emittance lattice in conjunction with emittance wigglers [17, 18] to squeeze out the maximum luminosity for all the beam current values which occur throughout a fill. Concocting a parameter list for “design luminosity” and designing the optics to achieve the corresponding emittance is *the first path to a machine with too large an emittance*.

If we now consider the *true* luminosity, experiment and simulation show us that, for large enough ξ_{yo} , ϵ_{yc} is blown up somewhat while ϵ_{xc} normally does not change significantly¹. The formula (30) for L_0 is an overestimate of the luminosity and is *the second path to a design with too large an emittance*.

¹In most rings, LEP being an exception.

Figure 2: Typical relationship between the unperturbed beam-beam tune-shift ξ_{y0} and the effective beam-beam parameter $\bar{\xi}$. The dashed line, $\bar{\xi} = \xi_{y0}$, corresponds to no beam-beam effects. Note that $\bar{\xi}/\xi_{y0} \rightarrow 1$ as $\xi_{y0} \rightarrow 0$.

Since the complexity of beam-beam phenomena [12, 13] cannot be meaningfully taken into account at this stage, we shall use a simple parametrised phenomenological model (as for LEP luminosity estimates in the design phase). According to this, the beam-beam effect reduces an unperturbed $\xi_{y0} \simeq 0.06$ to an effective saturated value $\bar{\xi} \simeq 0.04$ which may depend on other parameters such as the damping time (c.f. $\bar{\xi} = 0.04$ at BEPC [3]) giving a more realistic estimate

$$L = L_0 \frac{\bar{\xi}(\xi_{y0}, \tau_y, \dots)}{\xi_{y0}} = \frac{\pi k_b (1 + \kappa^2) f_0 (E/m_e c^2)^2}{r_e^2 \beta_y^*} \epsilon_x \xi_{y0} \bar{\xi}(\xi_{y0}, \tau_y, \dots). \quad (31)$$

Defining the bunch separation $S_b = c/f_0 k_b$, this can be expressed numerically as

$$[L/\text{cm}^{-2}\text{sec}^{-1}] = 1.09 \times 10^{38} \frac{(1 + \kappa^2) [E/\text{GeV}]^2 [\epsilon_x/\text{m}]}{[S_b/\text{m}] [\beta_y^*/\text{m}]}. \quad (32)$$

Again if it turns out that $\bar{\xi} > 0.04$ then a lower ϵ_x or higher I_b may be needed to reach the beam-beam limit and maximise L .

From (32), we can see that, as usual, high luminosity will be obtained with the help of:

Low β_y^* A tightly-focusing micro- β insertion can attain values $\beta_y^* \simeq 1$ cm using the gradients available (typically 30 T m^{-1}) from superconducting quadrupoles. However this generates a lot of chromaticity which has to be corrected and places constraints on the bunch length (see Section 3.5).

Minimum bunch spacing S_b For a given circumference, this is equivalent to storing as many bunches as possible. The smallest bunch spacing is determined by separation requirements connected with parasitic beam-beam interactions at the next bunch encounter at $s = S_b/2$ from the IP. All τ -Charm Factory designs have opted for a double ring with some kind of separation scheme.

Here again it is desirable to provide a range of possible k_b (machine commissioning will start with a single bunch and work up).

Large emittance ... but only once the necessary I_b has been achieved! The lattice should be designed with fairly large ϵ_x but include means to increase it (Robinson wigglers [19, 20] to vary damping partition, emittance wigglers, possibly variable tune optics).

For a constant optics, $\epsilon_x \propto E^2$ implies $L \propto E^4$. With ϵ_x constant (Robinson wigglers or emittance wigglers to offset the natural dependence), we can keep $L \propto E^2$ for lower energy or lower current operation.

Variable coupling The coupling compensation scheme for the detector solenoid will be tweaked to maximise luminosity.

3.4.2 MONOCHROMATOR OPTICS

In the case of a monochromator optics, the parameter choice is somewhat different. Here we follow the treatment of [5] to which the reader is referred for further details. We can still define the beam-beam strengths as in (28) except that the contribution of the energy spread dominates the vertical beam size in (9) and the beam is flat in the vertical plane:

$$\sigma_y^* \simeq D_y^* \sigma_\epsilon \gg \sigma_x^* = \sqrt{\epsilon_{xc} \beta_x^*}. \quad (33)$$

Not surprisingly, the beam-beam dynamics is considerably modified. According to pioneering studies [13, 21, 22] this results in a condition on the vertical beam-beam parameter:

$$\xi_{yo} \simeq \frac{(I_b/ef_0)r_e\beta_y^*}{2\pi(E_0/m_e c^2)D_y^{*2}\sigma_\epsilon^2} = \frac{(I_b/ef_0)r_e}{2\pi(E_0/m_e c^2)\mathcal{H}_y^*\sigma_\epsilon^2} \lesssim 0.015, \quad (34)$$

where $\mathcal{H}_y^* = D_y^{*2}/\beta_y^*$ is the value² of the vertical dispersion “invariant” which is constant between the IP and the first vertically bending element. According to the same studies, there is also a condition on the horizontal beam-beam parameter:

$$\xi_{xo} \simeq \frac{\beta_x^* \sigma_x^*}{\beta_y^* \sigma_y^*} \xi_{yo} \lesssim 0.05. \quad (35)$$

Therefore the emittance is determined by

$$\epsilon_{xc} \simeq \left(\frac{\xi_{yo}}{\xi_{xo}} \right)^2 \frac{\mathcal{H}_y^*}{\beta_y^*} \beta_x^* \sigma_\epsilon^2 \quad (36)$$

and tends to be small. Taking these conditions literally constrains the parameters rather tightly. However it is clear that even with a monochromator optics it is important to preserve as much flexibility as possible to cover the inevitable uncertainties in the analysis and estimation of parameters.

3.5 Bunch Length

Equations (32) and (34) show that small values of the β -functions at the IP are needed for high luminosity. This is arranged by means of strong final focusing of the beam in a low- β insertion. The stronger the focusing, however, the sharper the waist of the β -functions. And it is well known [12, 13] that the value of the smaller β should not be significantly less than the bunch length σ_z . So we must also satisfy

$$\sigma_z = \frac{c\alpha_c}{\omega_s E_0} \lesssim \begin{cases} \beta_y^* & \text{(standard optics)} \\ \beta_x^* & \text{(monochromator optics)} \end{cases}. \quad (37)$$

²It is assumed here that the optics is symmetric about the IP so that $\alpha_y = D_y^{*'} = 0$ at the IP itself.

Figure 3: Schematic layout of a proposed τ cF [6, 23]. Note the addition of a storage ring for the production of synchrotron light which could comfortably share the powerful injector system needed by the collider.

Since (for conventional lattices) the momentum compaction α_c is more or less determined ($\alpha_c \simeq 1/Q_x^2$) [10], the only way to get a sufficiently short bunch is to increase the synchrotron tune $Q_s = \omega_s/\omega_0 \propto \sqrt{V_{RF}}$ by applying a large RF voltage. A low-emittance monochromatic optics is at an advantage here over a standard high-emittance optics with its larger α_c .

Since various experiments and simulations suggest a range of values for the ratio, it is important to provide enough RF voltage to shorten the bunch to perhaps $\sigma_z/\beta_y^* \simeq 0.6$ although it is to be hoped that the collider can run closer to $\sigma_z/\beta_y^* \simeq 1$ to alleviate the problem of bunch-lengthening at high currents.

4 Designing the Collider

4.1 General Configuration

We have seen that a τ -Charm Factory should be a double-ring collider with many bunches. The question of how many interaction points it should have is often brought up. Although this depends partly on whether a single detector is adequate for the anticipated physics programme, there are strong arguments for a single interaction point on the basis of performance. Experience has shown that the total tune-spread from beam-beam interactions comes into the determination of ξ . Moreover, with a single IP, the spectrum of coherent beam-beam modes is as simple as can be since each bunch is only aware of the presence of a single bunch in the other beam.

Most designers of a τ -Charm Factory [2, 23, 24, 25, 26, 27, 28, 6, 29, 30, 8, 7, 9, 31] have chosen a head-on collision geometry with an electrostatic separation scheme in the vertical plane. Notable exceptions include [32, 5] which use a combination of horizontal and vertical separation and [33, 34] which have crossing angles in the horizontal plane.

A layout of the accelerator complex from [6] is shown in Figure 3. It includes a synchrotron light source which could be built to take advantage of the powerful positron injector system. Filling a light source storage ring (of energy around 2 GeV) would take only a small part of the duty cycle of the injectors [26, 23, 35].

In contrast to the earlier generations of e^+e^- rings, about half the circumference is devoted to the two straight sections. With many bunches in two rings, there is no longer any need to maximise the revolution frequency *per se* and we shall see that the long experimental straight section is necessary to properly match its optics. On the other side of the ring, the space provided by the long utility straight section is useful for a number of purposes.

In this layout, newly-injected electrons and positrons must make almost a full turn before reaching the interaction region, thereby minimizing detector backgrounds during injection. This leaves open the option of injection into synchrotron phase space at a dispersive location to eliminate transverse oscillations of the injected beam in the experimental straight section. If the backgrounds can be kept low enough, then this may open the possibility of topping up the stored beam during physics data-taking.

An additional benefit of having two rings, is that at the price of some asymmetry between them, radiation-sensitive elements such as the superconducting RF cavities and the detector can always be placed *upstream* of the principal sources of synchrotron radiation (wigglers, arc dipoles).

4.2 Arc Optics

Most τ cF designs have used conventional FODO cells in the main arcs. These are most economical in space and can be equipped with sextupoles to correct chromaticity in the well-known way. Correction with just two sextupole families can provide adequate dynamic aperture [23, 26] and can be tuned to a variety of different phase advances per cell in order to vary ϵ_x : $(\mu_x, \mu_y) = (60^\circ, 60^\circ), (60^\circ, 90^\circ), (90^\circ, 90^\circ) \dots$. Alternatives to this traditional scheme will be discussed in Section 5.3. More sextupole families may improve dynamic aperture but would have to be powered differently for different (μ_x, μ_y) . Since the basic ideas are rather well-known, we shall not discuss FODO-based schemes in much more detail.

Injection insertions with fast kickers and non-zero dispersion (see above) should be incorporated into the arcs.

4.3 Dispersion Suppressors

The arcs must be connected to the dispersion-free straight sections by suitable dispersion suppressors. The simplest scheme with half the normal bend angle per cell and quadrupoles in series with arc only works for $\mu_x = 60^\circ$. A more flexible scheme with several independent power supplies (c.f. LEP's [36]) is needed if (μ_x, μ_y) are to be variable.

Emittance (pure dipole) and Robinson (combined-function dipole-quadrupole) wigglers, which both need large values of D_x , can be included in these insertions. Such devices produce

a vertical tune-shift $\Delta Q_y \propto B^2/E_0^2$ from edge-focusing which must be compensated with the nearby quadrupoles.

4.4 Utility Insertions

The dispersion-free utility insertion has a number of purposes. It can house the RF cavities and damping wigglers to increase injection efficiency or reduce emittance. This linear optics of this part of the ring will also be used to adjust the tunes and make other compensations. One attractive and flexible idea is to construct it from a set of quadrupole triplets as in [5]. This can be used to provide low β -functions at the locations of RF cavities or wigglers. Other designs use a string of FODO cells.

4.5 Interaction Region

The most complicated part of the lattice is the experimental insertion consisting of a micro- β insertion and separation scheme. Unlike the other parts of the ring discussed above, it must change substantially in the transition from standard to monochromator optics.

4.5.1 STANDARD OPTICS

Most designs use doublet or triplet focusing to achieve $\beta_y^* \simeq 1$ cm. Engineering solutions for this could be based on iron-free superconducting quadrupoles in a common cryostat protruding into the detector or on a hybrid consisting of small permanent magnet quadrupoles as close as possible to the IP, backed up with superconducting coils [37]. The idea of the latter solution is to prevent excessive growth of $\beta_y(s) = \beta_y^* (1 + s^2/\beta_y^{*2})$ by starting the focusing some 15 cm closer to the IP than the end of the cryostat would be in a pure superconducting scheme. However it raises questions of field quality and engineering construction which are beyond the scope of this lecture. The detector design allows the closest quadrupole to approach to $L_1 = 0.8$ m with an outer radius not greater than 20 cm.

The micro- β insertion must also incorporate a scheme to compensate the betatron coupling generated by the detector solenoid. There are a variety of possibilities for this:

- Compensating solenoid coils, wound around the quadrupoles, to directly cancel the solenoid effects. This is the most attractive scheme but it remains to be seen if it can be made compact enough for the solid-angle requirements of the detector.
- Dedicated skew quadrupoles interspersed with the focusing quadrupoles have the disadvantage of increasing the distance to the electrostatic separator.
- Rotatable micro- β quadrupoles as used with success in CESR. However the construction of separately rotatable *superconducting* quadrupoles inside their common cryostat would be another technical challenge [37].

As soon as possible after the micro- β quadrupoles, the beams must be separated into their two rings. The separation can be initiated with electrostatic (or, perhaps, RF-magnetic) separators. The amount of this initial separation is limited by the integral of the vertical electric field over the separator. The peak value (at the top energy of the collider) of this should be kept below about 2 MV m^{-1} to minimise the risk of sparking, especially if there is

a significant quantity of synchrotron radiation³. Once the separation is sufficient, these can be followed with a suitable vertically bending septum magnet. Further vertical bends finish the separation and bring the two beams back onto horizontal orbits in their respective rings. The vertical dispersion thus generated has to be matched to zero before the beams enter the horizontal dispersion suppressors. This requires a vertical phase advance shift $\Delta\mu_y \simeq 2\pi$ between the separator and the final vertical dipole [38, 26, 5]. Several similar interaction region optics have been worked out. Figure 4 is typical.

The overall length of the common part of the rings determines the minimum totally safe⁴ bunch spacing. In practice, encounters are allowed at distances where the beams are separated by $\gtrsim 10\sigma_x$ which is enough to reduce the parasitic beam-beam effects to an acceptable level. For separation at the top energy (say, 2.2 GeV) the minimum bunch spacing works out to be $S_b \simeq 12\text{m}$ in typical cases [2, 23, 25, 26, 31]. This means that the first encounter takes place some 6 m from the IP, a point which may be inside the electrostatic separator.

4.5.2 MONOCHROMATOR OPTICS

In the τcF , the necessary vertical dispersion can be generated in the vertical separation scheme. Since the initial separation is electrostatic, this dispersion naturally has opposite signs for the two beams. As seen from (25) and (34), the performance of the scheme hinges on being able to generate a large value of $\mathcal{H}_y^*$ at the IP. A large β_y in the vertical bends helps to achieve this.

5 Examples of τ -Charm Factory Design

5.1 The CERN-Spain τ -Charm Factory

This design [6, 40] evolved from early high-emittance designs [2, 24] but was drastically modified [5] to make it compatible with a monochromator scheme and longitudinal polarization in further stages. The general layout was already shown in Figure 3.

5.1.1 OVERALL PARAMETERS

Table 1 gives two parameter lists for this collider. The first is for the standard high-luminosity, high-emittance optics at $E_0 = 1\text{ GeV}$ where the luminosity should be largest and the second corresponds to the monochromatic configuration at $E_0 = 1.5\text{ GeV}$.

Since the requirements on the superconducting RF cavities of the τcF overlap those of the LHC, the RF frequency in this design was made equal to that of the LHC to open the possibility of shared development and testing. The circumference is chosen to allow considerable flexibility in the number of stored bunches [27], not only for this RF frequency but also

³This may have several sources: the vertical bends, micro- β quadrupoles, etc. The design of the interaction region must be carried out in parallel with a detailed study of such sources to estimate detector backgrounds and other unwanted effects like separator sparking.

⁴In the sense that each bunch only ever experiences fields from bunches of the opposing beam in the collision process at the IP.

Figure 4: Interaction region optics for a standard high-emittance optics, showing $\sqrt{\beta_x}$, $\sqrt{\beta_y}$ and the vertical dispersion D_y . In this and similar plots (made by the optics program MAD [39]) horizontally (vertically) focusing quadrupoles are shown as boxes above (below) the beam axis and bending magnets or electrostatic separators are shown as boxes straddling the beam axis. In this case, the first such box is the electrostatic separator and the others are the vertical bending magnets.

Table 1: Parameter lists for the CERN-Spain τ cF [6, 5]. Parameters for the standard high luminosity phase are quoted at the energy just above the τ -pair production threshold where maximum luminosity is required. For the monochromatic phase the relevant energy is that of the J/ψ resonance.

Quantity		Standard	Monochr.	Units
Nominal Beam Energy	E	2	1.5	GeV
Circumference	C	360		m
Revolution frequency	f_0	832.76		kHz
Bending radius	ρ	11.8		m
β -function at IP	β_x^*	0.2	0.01	m
	β_y^*	0.01	0.15	m
Betatron tunes	Q_x	9.3	17.28	
	Q_y	9.2	10.18	
Momentum compaction	α	0.020	0.0036	
Natural horizontal emittance ($J_x = 1$)	ϵ_x	108	20	nm
Emittance with wigglers etc.		300	10	nm
Vertical emittance		7	2	nm
Fractional energy spread	σ_e	4.5×10^{-4}	8×10^{-4}	
Radiative energy loss per turn	U_0	130	70	keV
Radiation damping times	τ_x	70	26	msec
	τ_y	35	52	msec
	τ_e	14	26	msec
RF frequency	f_{RF}	399.72339		MHz
RF voltage	V_{RF}	8.0	2.3	MV
Synchrotron tune	Q_s	0.077	.02	
Number of bunches	k_b	30		
Bunch spacing	S_b	12		m
Total current per beam	I	573	315	mA
Particles per bunch	N_b	1.37×10^{11}	0.8×10^{11}	
Radiated power per beam	P_{rad}	75	22	kW
RMS bunch length	σ_z	6.6	8	mm
Longitudinal impedance ($\omega \rightarrow 0$)	$ Z/n _0$	$\simeq 1.0$		Ω
Longitudinal impedance (effective)	$ Z/n _{\text{eff}}$	$\simeq 0.13$	0.17	Ω
Beam-beam parameters	ξ_x	0.04	0.04	
	ξ_y	0.039	0.014	
Lifetime	τ	$\simeq 4$	1	hours
Luminosity	L	1×10^{33}	4×10^{32}	$\text{cm}^{-2}\text{sec}^{-1}$
CM energy spread	σ_w	1.3	0.10	MeV

Figure 5: Example of emittance reduction by adding “missing quadrupoles” to make two FODO cells out of one (following [5]). In both cases, the horizontal and vertical phase advances are 90° although $\mu_y = 60^\circ$ was used in [5] as it is advantageous for dynamic aperture.

for the more common $f_{RF} = 500$ MHz should it eventually be used. For the circumference of 360 m, these lead to harmonic numbers $h = 480$ and $h = 504$ both of which have many factors, allowing a wide choice of bunch numbers.

5.1.2 HIGH AND LOW EMITTANCE

In this design, the reduction of the natural emittance (with no wigglers and horizontal damping partition number $J_x = 1$) from 100 nm to 20 nm between the two phases is achieved by means of a special design of the standard arc cells. The length of these FODO cells is halved by adding additional quadrupoles in spaces left in the middle of the bending magnets as shown in Figure 5. The reduction of the dispersion function provides a significant reduction in the emittance. In the high-emittance optics, the emittance can be further increased (when there is sufficient beam current to warrant it) with emittance and Robinson wigglers to reduce J_x . In the monochromatic case, damping wigglers (in locations with zero dispersion) and Robinson wigglers (now working in the opposite direction to increase J_x) are used to reduce the emittance still further.

A disadvantage of this scheme of halving the cell length is that it becomes very difficult to find space for additional elements such as sextupoles, corrector magnets, beam-position monitors (BPMs), vacuum pumps, etc. Since some of the lattice options are to have $\mu_x = 90^\circ$, it is important to have more than one BPM per cell to ensure adequate sampling of the orbit. The only way to pursue this approach seems to be to make the cells longer and accept a larger circumference. An alternative is to reduce the emittance simply by varying the phase advance in a fixed FODO cell layout. This approach has been followed in [7, 31] where a factor of 3

reduction in emittance is obtained by changing from $\mu_x = \mu_y = 90^\circ$ to $\mu_x = \mu_y = 60^\circ$ (this is similar to what has been done in practice in LEP [18]).

The dispersion suppressor optics, which is similar to the LEP design [36] and shown in Figure 6 is sufficiently flexible to deal with dispersions in the different arc optics.

5.1.3 INTERACTION REGION

For the Standard case, the optics in the straight section is similar to that shown in Figure 4. For the monochromatic case, the interaction region scheme (Figure 7) is based on that presented (for more extreme conditions of emittance) in [32]. This design incorporates further special features:

- The initial electrostatic separation is *horizontal*. Once they are sufficiently separated the beams are separated vertically by bending magnets.
- The bulk of the correction of the chromaticity of the micro- β insertion is done locally using *electrostatic sextupoles* to take advantage of the opposite sign dispersion which exists near the IP.

Although there are some technical challenges associated with this concept, the 3D separation scheme offers advantages for background screening and the design of the first vertical bending magnet. Other monochromatic insertion designs separate only in the vertical plane [7, 8, 9, 30]

5.1.4 BEAM LIFETIME

The beam lifetime in the two cases is determined by different effects: In the Standard case, beam-beam bremsstrahlung is the dominant loss mechanism. In the Monochromatic case the high beam density, particularly in the interaction region, causes the Touschek effect to dominate [41, 5].

5.1.5 LONGITUDINAL POLARIZATION

The final stage of the collider proposed in [5] further extends the physics reach of the monochromator scheme with longitudinally polarized beams at the IP. This scheme is based on ideas in [42, 43] and does not involve the usual radiative self-polarization in the collider. Instead the beams are pre-polarized in special rapidly-polarizing (i.e., high magnetic field) accumulation rings (an upgrade of the injection system ...) and then injected through spin-rotators in the transfer lines so that their polarization is in the horizontal plane of the collider. The initial angle with respect to the orbit is chosen so that the precession around the vertical axis brings the spins into the longitudinal direction at the IP. A compact superconducting solenoid in the utility insertion further rotates the spin around the longitudinal direction so that the total spin-tune (number of precessions per turn) is exactly $1/2$. This ensures that the polarization will again be longitudinal on the next turn. An analysis of the depolarizing effects [5] shows that a decent level of longitudinal polarization can be maintained for the duration of a fill. For further details, we refer the reader to [5].

Figure 6: Dispersion suppressor and an arc cell in the monochromatic optics of [5]. The Robinson wigglers to vary J_x are installed in a high dispersion location.

Figure 7: Optics of the experimental insertion from [5]; the small horizontal dispersion generated by the initial separation in that plane is not shown.

5.2 Monochromator with Flat Beams

Early ideas for monochromatic colliders [14, 16] considered the introduction of vertical dispersion as a modification of the usual flat beam collision scheme with $\beta_y^* \ll \beta_x^*$. It may seem attractive to try to implement such a scheme as a relatively minor modification of the Standard scheme. However it has been shown [44] that this procedure leads to a number of difficulties including an awkward geometry and poorer performance than can be expected with schemes using beams flattened in the vertical plane. Most authors are therefore developing schemes of the latter type.

5.3 Non-FODO Arc Cells

Storage rings designed for the production of synchrotron light from insertion devices such as wigglers and undulators require low emittances. Their designs have departed from the FODO cell structure used for nearly all the high-energy physics colliders (see, e.g., [45] for a review). Instead, a variety of achromatic modules can be used as the basic lattice units. In this context, achromatic means that the dispersion function is zero at the entrance and exit of the module.

A recent study [9], from which the examples in this section are taken has shown how some of these, namely the Double-Bend Achromat (DBA) and Triple-Bend Achromat (TBA) can be used to construct flexible optics for a two-phase τ cF. The optics of high- and low-emittance versions of these basic modules is shown in Figures 8–11.

Achromatic arc modules eliminate the need for a dispersion suppressor since the dispersion is automatically matched to zero at the ends of each module. An exception to this among the four cases shown in Figures 8–11 is the high-emittance DBA lattice where it is necessary to allow the dispersion to be non-zero at the ends of the module to achieve a large contribution to the emittance. This allows $\mathcal{H}_x$ to increase in the bending magnets. The dispersion is finally suppressed by a special matching of the last module in each arc as shown in Figure 12.

In the TBA lattice, the change in emittance is achieved by a simple rematching with the quadrupoles which changes $\mathcal{H}$ dramatically in the bending magnet in the centre of the achromat.

These lattices use a straightforward FODO structure for the utility insertion.

The parameters obtained by this set of lattices are given in Table 2. In each case, just rematching the basic lattice module changes the emittance by an order of magnitude. Further factors can be achieved by additional measures, such as wigglers or damping partition number modification. To allow a straightforward comparison, these are not included in the parameters given in Table 2.

6 Summary

There is now a broad convergence of the various design studies, in that most workers are now trying to follow the two-stage concept of a Tau-Charm Factory: a high-emittance, high luminosity initial phase followed by a more adventurous, low-emittance, monochromatic second phase. Designing a collider capable of both of these is highly demanding and will

Figure 8: Square roots of the β -functions and horizontal dispersion in the mis-matched DBA module for a high-emittance lattice.

Figure 9: Square roots of the β -functions and horizontal dispersion in the DBA module for a low-emittance lattice.

Figure 10: Square roots of the β -functions and horizontal dispersion in the TBA module for a high-emittance lattice.

Figure 11: Square roots of the β -functions and horizontal dispersion in the TBA module for a low-emittance lattice.

Figure 12: Dispersion functions in half the ring for the high-emittance DBA lattice.

Table 2: Performance of the Double- and Triple-Bend Achromat lattices in their two modes of operation.

Quantity		DBA		TBA		Units
		Standard	Monochr.	Standard	Monochr.	
Nominal beam energy	E_0	2.0	2.0	2.0	2.0	GeV
Circumference	C	360.9	360.9	444.2	444.2	m
Revolution frequency	f_0	0.831	0.831	0.675	0.675	MHz
Bunch frequency	$k_b f_0$	24.93	24.93	20.25	20.25	MHz
Energy spread	σ_e	5.6×10^{-4}	5.6×10^{-4}	7.0×10^{-4}	7.0×10^{-4}	
Natural emittance	ϵ_{x0}	170	17	100	12	nm
	ϵ_{y0}	5.6	1.2	3.3	0.8	nm
Optical function at IP	β_x^*	0.3	0.01	0.3	0.01	m
	β_y^*	0.01	0.15	0.01	0.15	m
	D_y^*	0.0	0.32	0.0	0.32	m
Natural chromaticities	Q'_x	-44.973	-56.531	-32.667	-47.756	
	Q'_y	-35.548	-44.134	-41.109	-47.627	
Sextupole strengths	SF	-18.03	-126.48	-27.83	62.78	T/m
	SD	52.17	117.83	14.18	-104.07	T/m
Dynamic aperture in x		46	21	33	17	$\sigma_{\beta x}^*$
Dynamic aperture in y		20	22	139	40	$\sigma_{\beta y}^*$
CM energy resolution	σ_w	1.67	0.114	1.998	0.098	MeV
Gain factor	λ	1.0	14.5	1.0	20.4	
Beam current	I_b	0.245	0.354	0.102	0.302	A
Beam-beam strength	ξ_x	0.04	0.04	0.04	0.04	
	ξ_y	0.04	0.04	0.04	0.029	
Luminosity	L	4.4×10^{32}	6.7×10^{32}	2.2×10^{32}	5.6×10^{32}	$\text{cm}^{-2}\text{s}^{-1}$

require a good deal of work yet. However a number of promising lattices are in the air, among them some which depart from the FODO arcs traditional for colliders. In this flow of ideas we see the synchrotron light sources beginning to pay back their debt to the high-energy colliders. We also see that the intellectual challenges and scope for innovation in the field of e^+e^- storage rings are far from being exhausted.

Anyone embarking on a project must never forget that, since the feasibility of a monochromatic scheme will not be demonstrated until someone actually builds one, the initial high-luminosity phase, which is difficult enough already, should not be compromised.

Acknowledgements

I would like to thank the many colleagues with whom I have worked over the years on the design of the τ -Charm Factory. Special mention must be given to Joel Le Duff, Jasper Kirkby, Marc Muñoz, Juan-Antonio Rubio, Carlos Willmott and Alexander Zholents. The material for Section 5.3 was very kindly supplied by Angeles Faus-Golfe.

References

- [1] J. Kirkby, "A τ -Charm Factory at CERN", CERN-EP/87-210 (1987), and Proc. Int. School of Physics with Low-Energy Antiprotons on Spectroscopy of Light and Heavy Quarks, Erice, Sicily, 1987 (Plenum Press, New York, 1989) 401.
- [2] J.M. Jowett, "Initial Design of a τ -Charm Factory at CERN" CERN LEP-TH/87-56 (1987).
- [3] C. Zhang, "BEPC: Status and Performance", Proc. XVth International Conf. on High Energy Accelerators, Hamburg, 20-24 July 1992, Int. J. Mod. Phys. A (Proc. Suppl.) 2A (1993) 439.
- [4] E.M. Gonzalez Romero and J.I. Illiana, "CP Violation Study in the Processes $e^+e^- \rightarrow J/\psi \rightarrow \Lambda\bar{\Lambda}$ and $J/\psi \rightarrow \Xi^-\Xi^+$ ", in [27].
- [5] A. Zholents, "Polarized J/ψ Mesons at a Tau-Charm Factory with a Monochromator Scheme", CERN SL/92-27 (AP) (1992).
- [6] J.M. Jowett, A. Zholents, C. Fernandez-Figueroa, M. Munoz, J.-M. Quesada, C. Willmott, "The Tau-Charm Factory", same volume as [3] 439.
- [7] P. Beloshitsky, "A Magnet Lattice for a τ -Charm Factory Suitable for both Standard Scheme and Monochromatization Scheme", Orsay Report, LAL/RT 92-09 (1992).
- [8] M.V. Danilov *et al*, "Conceptual Design of Tau-Charm Factory in ITEP", same volume as [3] 455.
- [9] A. Faus-Golfe and J. Le Duff, "A Versatile Lattice for a τ -Charm Factory that includes a Monochromatization Scheme (Low Emittance) and a Standard Scheme (High Emittance)", Proc. Particle Accelerator Conf., Washington May 1993 (to appear).
- [10] M. Sands, "The Physics of Electron Storage Rings", SLAC-PUB 121 (1970).
- [11] J.M. Jowett, in M. Month and M. Dienes (Eds.), "Physics of Particle Accelerators", AIP Conf. Proc. 153 (1987) 864.

- [12] R. Siemann, this school.
- [13] A.A. Zholents in M. Dienes, M. Month, S. Turner (Eds.), *Frontiers of Particle Beams: Intensity Limitations*, Springer-Verlag, Berlin 1992.
- [14] A. Renieri, Frascati Preprint /INF-75/ 6 (R), (1975).
- [15] I.Ya. Protopopov, A.N. Skrinsky and A.A. Zholents, "Monochromatization of Colliding Beam Interaction Energy in Storage Rings", Proc. 5th All-Union Conf. on Charged Particle Accelerators, Dubna, 1978, (Dubna, 1979) 132.
- [16] A.A. Avdienko et al., Proc. 12th International Conf. on High Energy Accelerators, Batavia, 1983.
- [17] J.M. Jowett and T.M. Taylor, "Wigglers for Control of Beam Characteristics in LEP", IEEE Trans. Nucl. Sci. **30** (1983) 2581.
- [18] J. Poole (Ed.), "Proc. Third Workshop on LEP Performance", Chamonix, January 11-16, 1993, CERN SL Report, to appear 1993.
- [19] K.W. Robinson, "Radiation Effects in Circular Accelerators", Phys. Rev. **111**, 373 (1958).
- [20] Y. Baconnier, R. Cappi, J.-P. Riunaud, H.H. Umstätter, M.P. Level, M. Sommer, H. Zyngier, Nucl. Instr. and Methods **A234** (1985) 244.
- [21] A.L. Gerasimov and A.A. Zholents, "Beam-Beam Effects in Storage Rings with Monochromator Scheme", Proc. 13th International Conf. on High Energy Accelerators, Novosibirsk, 1986, (Novosibirsk, 1987) 82.
- [22] A. Gerasimov, D. Shatilov and A. Zholents, "Beam-Beam Effects with a Large Dispersion at the Interaction Point", Nucl. Instr. and Meth., A305, No.1, (1991)25.
- [23] W.T. Kirk and M.L. Perl (Eds.), "Proc. Tau Charm Factory Workshop", SLAC, California, 23-27 May 1989, SLAC Report 343 (1989).
- [24] J.M. Jowett, "The τ -Charm Factory Storage Ring", Proc. 1st European Particle Accelerator Conf., Rome, 7-11 June, 1988, World Scientific, Singapore, 1989, p. 368.
- [25] B. Barish *et al*, "Tau-Charm Factory Design", SLAC-PUB 5180 (1990).
- [26] J. Gonichon, J. Le Duff, B. Mouton, C. Travier, "Preliminary Study of a High Luminosity e^+e^- Storage Ring at a C.M. Energy of 5 GeV", Orsay Report, LAL/RT 90-02 (1990).
- [27] J.M. Jowett in J. Kirkby and J.-M. Quesada (Eds.) Proc. Meeting on the τ -Charm Factory Detector and Machine, Univ. of Seville, 29 April-2 May 1991.
- [28] V.S. Alexandrov et al., "JINR Tau-Charm Factory Design Considerations", Proc. IEEE Particle Accelerator Conf., San Francisco, 6-9 May 1991, 195.
- [29] V.A. Bednyakov, G.A. Shelkov (Eds.), "Proc. of the Workshop on JINR C-Tau Factory", 29-31 May 1991, JINR, Dubna 1992.
- [30] E.A. Perelstein *et al*, "JINR Tau-Charm Factory Study", same volume as [3] 448.
- [31] M. Munoz, private communications, to be published.

- [32] Yu.I. Alexahin, A.N. Dubrovin and A.A. Zholents, "Proposal on a Tau-Charm Factory with Monochromatization", Proc. 2nd European Particle Accelerator Conf., Nice, 1990 (Éditions Frontières, 1990) 398.
- [33] K. Oide, in [23].
- [34] Y. Alexahin, "On the Scheme of Monochromatic τ -Charm Factory with Finite Crossing Angle", private communication, to be published.
- [35] J. Le Duff, this school.
- [36] A. Hutton, M. Placidi, T.M. Taylor, "Improvements to the LEP Lattice Design", same volume as [16] 164.
- [37] T.M. Taylor, private communications.
- [38] M. Donald and A. Garren, in [23].
- [39] H. Grote, F.C. Iselin, "The MAD Program, Version 8.10, User's Reference Manual", CERN/SL 90-13 Rev. 3 (1992).
- [40] J. Kirkby, "Physics and Design of the Tau-Charm Factory in Spain", CERN-PPE/92-30; Int. Workshop on Electroweak Physics Beyond the Standard Model, Valencia, Spain, 2-5 October 1991.
- [41] J. Le Duff, "Single and Multiple Touschek Effects", CERN Accelerator School, Berlin, 14-25 September 1987, CERN 89-01 (1989).
- [42] Ya.S. Derbenev and A.M. Kondratenko, "Acceleration of Polarized Particles", Soviet Physics Doklady, **20** (1975/1976) 562.
- [43] Ya.S. Derbenev et al., "Project of Obtaining Longitudinal Polarized Colliding Beams in Storage Ring VEPP4 at 2 GeV", Proc. 12th International Conf. on High Energy Accelerators, Fermilab (1983) 410.
- [44] A. Faus-Golfe and J. Le Duff, "A Versatile Lattice for a τ -Charm Factory that includes a Monochromatization Scheme", LAL/RT 92-01 (1992).
- [45] A. Ropert in CERN Accelerator School on "Synchrotron Radiation and Free Electron Lasers", CERN Report 90-03 (1990).