PROPOSAL ON A TAU-CHARM FACTORY WITH MONOCHROMATIZATION

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Abstract: A concept of the tau-charm factory is proposed which provides a high luminosity and small centre-of-mass energy spread in the electron-positron collisions due to vertical beams decomposition with respect to particle energy.

Introduction

Since 1979 the idea has been discussed of a dedicated e^+e^- collider with the centre-of-mass energy $W = 3\div5$ GeV for investigation of charmed particles and τ-leptons[1]. Several studies of such a collider, called the tau-charm factory (τcF), were made in CERN[2] and SLAC[3,4].

The present proposal follows the double-ring multibunch concept of the previous τcF designs, but differs from them by the monochromator scheme of e^+e^- collisions which reduces the centre-of-mass energy spread, σ_W, to the value smaller than the J/ψ and ψ' meson widths.

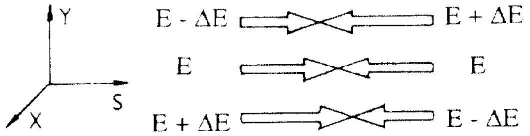

Fig. 1. Monochromatization principle.

Basic relations

Monochromatization of e^+e^- collisions in the τcF is achieved by introduction of a dispersion function at the interaction point (IP) with opposite signs for electrons and positrons[5] (see Fig. 1). The monochromator scheme permits to obtain a large dispersion with low beta-function[6] and reduces mixing of particles with different energies inside the beam by betatron oscillations. Low beam emittances serve to the same purpose. As a result σ_W becomes practically insensitive to the beam energy spread, σ_E, and equals to

$$\sigma_W = E_0\sqrt{\frac{2\varepsilon_y\beta_y^*}{\psi_y^{*2}}}\,, \tag{1}$$

where E0 is nominal beam energy, ε_y is vertical emittance, ψ_y, β_y are vertical dispersion and betatron functions at the IP.

As it follows from the expression

$$L = \frac{f_c N^2}{4\pi\sigma_x^*\sigma_y^*} \simeq \pi f_c\left(\frac{E_0\sigma_E}{e^2}\right)^2\frac{\psi_y^{*2}}{\beta_y^*}\,\frac{\xi_x\xi_y}{\beta_x^*}\,, \tag{2}$$

derived in the approximation of a flat beam with dimensions

$$\sigma_x^* = \sqrt{\varepsilon_x\beta_x^*} \ll \sigma_y^* \simeq |\psi_y^*|\sigma_E\,, \tag{3}$$

the luminosity can be maximized by increasing energy spread σ_E instead of the horizontal emittance ε_x, which was the case in the previous designs[2-4]. In eq. (2) the following notations were introduced: the collision frequency f_c, number of particles per bunch N, electronic charge e, horizontal β-function value at the IP β_x^*, and linear beam-beam tune shifts

$$\xi_i = \frac{e^2 N\beta_i^*}{2\pi E_0\sigma_i^*\sigma_y^*}\,,\quad i = x, y \tag{4}$$

From both experimental and simulation data[7,8] it is known that to secure the beam stability against the beam-beam driven synchro-betatron resonances, the tune-shift in the direction of energy decomposition should be reduced to values $\xi_y = 0.01\div0.02$ which are a factor of 4 lower than maximal values achieved so far.

From the first look at the eq. (2) it seems that decrease in ξ_y should result in fall of luminosity. In fact it is tune shift for the minor beam dimension, ξ_x, which matters, as an alternative representation for luminosity shows:

$$L = \frac{IE_0}{2e^3}\,\frac{\xi_x}{\beta_x^*}\,, \tag{5}$$

where I is current per beam. Recent simulation[8] has shown that ξ_x is only slightly affected by monochromatization.

To preserve ξ_x with enlarged σ_y^* one should increase N and/or diminish σ_x^*, the latter requires a low emittance lattice. The possibility to increase N (and I) is limited by the coherent stability requirements. For the optimum design limitations on both ξ_x and I are reached simultaneously.

Final focus and monochromator scheme

As follows from eqs. (1,2) both luminosity L and energy resolution require a large value of the ratio

$$J_y^* = \frac{\psi_y^{*2}}{\beta_y^*} \tag{6}$$

The accepted double-ring configuration with vertical separation presents a possibility to generate large J_y at vertical bends. It is evident from the symmetry considerations that arising dispersion function has opposite signs for electrons and positrons.

Fig. 2 shows optics of the experimental insertion which provides $J_y^* = 1.07$ m due to large β_y value at the vertical bending magnets VM1-VM3. In order to minimize excitation of vertical beam emittance by quantum fluctuations the bending field decreases as J_y grows from VM3 to VM1.

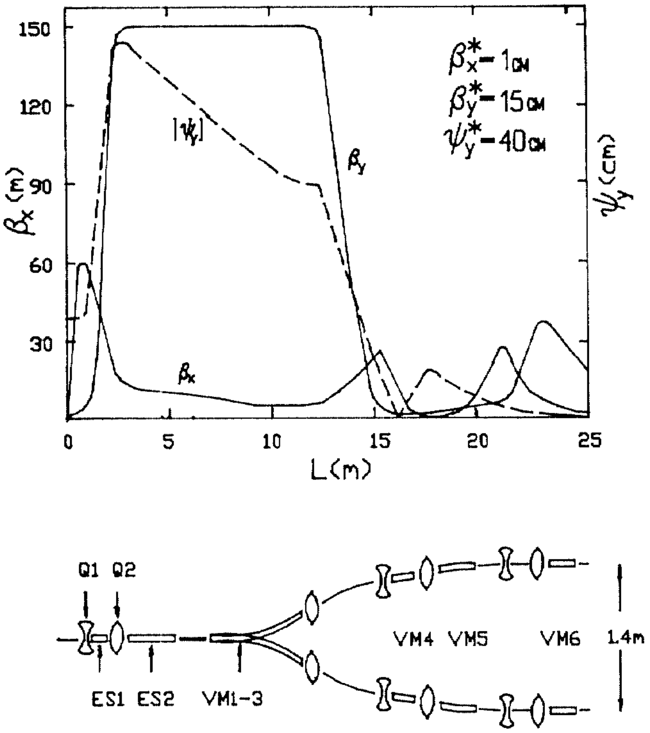

Fig.2. The experimental insertion optics. Denoted are: final focus lenses Q1,Q2, common to both beams; electrostatic separators ES1,ES2; vertical bending magnets VM1-VM6.

A doublet of quads Q1, Q2 provides enough focusing to obtain $\beta_x^* = 1$ cm, $\beta_y^* = 15$ cm. They are placed at distances 0.65 m and 2.1 m from the IP in accordance with the detector requirements and the desire to put electrostatic separator with a sextupole component ES1 as close to the IP as possible.

Orbit separation

Electrostatic separators ES1, ES2 (Fig.3)produce the initial horizontal separation. Due to the small β_x (see Fig.2) and correspondingly, small σ_x, the beams can be shielded from each other immediately after the second separator, ES2, where the horizontal spacing between the orbits in the considered variant reaches 2 cm for 2 MV/m separating field. This makes acceptable the bunch frequency of 30 MHz. The orbits are further separated vertically by the magnets VM1-VM6. The synchrotron radiation, generated in the VM1 magnet passes between the separator plates and hits the SR absorber, placed in a special pocket so that separator plates be protected from the photoelectrons. Owing to this the electric field strength of up to 3 MV/m and more may be feasible, permitting to further increase collision frequency and luminosity.

Chromaticity correction

Correction of the betatron tunes chromaticity in the storage ring (the main contribution to which is made by the final focus lenses), is significantly facilitated by the non-zero dispersion function in the interaction region. This offers a possibility to compensate for the chromatic perturbations right in the place of their origin, considerably simplifying a number of problems connected with the sextupole arrangement, such as providing dynamic aperture and elimination of chromatic dependence of the betatron and dispersion functions.

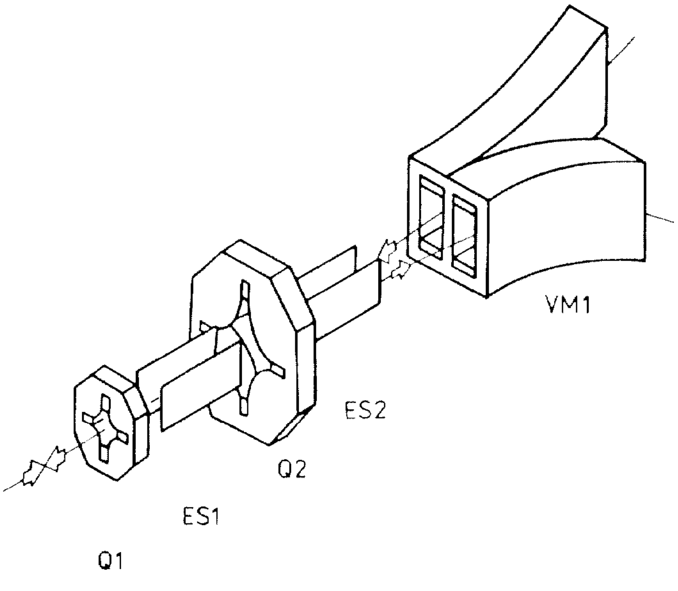

Fig.3. Bunch separation scheme.

Difference in sign of the dispersion function for electrons and positrons in the final focus region makes it necessary to use here an electrostatic sextupole, which can be combined with the ES1 separator plates (Fig.4). The obtained sextupole field gradient of about 6 kV/cm^3 is sufficient to compensate for the horizontal chromaticity of the final focus lenses due to large ψ_y. The vertical chromaticity is corrected with magnetic sextupoles placed after the VM3 magnets, separately for each beam.

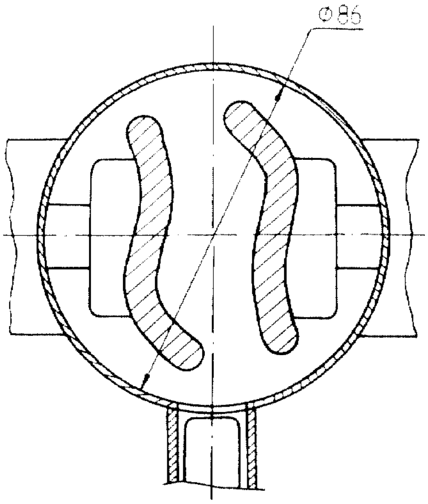

Fig.4. Profile of the ES1 separator plates, chosen to obtain 6 kV/cm^3 sextupole component with a 20 kV/cm homogeneous field.

The residual chromaticity is compensated with sextupoles in the arc cells. The dynamic aperture, calculated for energy oscillation amplitude $\Delta E/E_c = 1\%$ is shown in Fig.5.

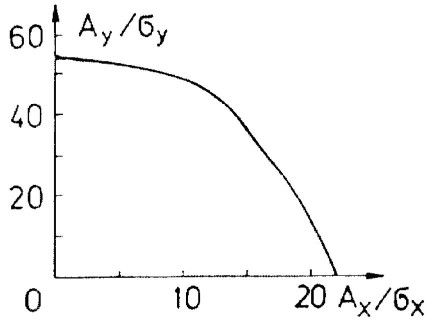

Fig. 5. The τcF dynamic aperture. The graph shows maximal stable betatron amplitudes for particles with energy oscillation amplitude $\Delta E/E_0$ = 1%. Normalizing values $\sigma_{x,y}$ correspond to ε_x = 4 nm·rad and ε_y = 0.2 nm·rad.

τcF main parameters

Maximum beam energy E_0 (GeV)	2.5
Circumference C (m)	300
Emittances $\varepsilon_x/\varepsilon_y$ (nm·rad)	3.6/0.2
Energy spread σ_E (%)	0.1
Momentum compaction factor, α	0.002
Bunch length σ_s (cm)	0.75
Number of bunches per beam	30
Particles number per bunch, N	$1.2\cdot10^{11}$
Beam current, I (mA)	580
Energy loss per turn (keV)	400
Damping time (ms)	6
Longitudinal threshold impedance, $\lvert Z_n\rvert/n$ (Ohm)	0.1

RF system parameters

Frequency (MHz)	500
Accelerating voltage (MV)	2.5
Number of cavities per ring	6
Dissipated power (kWt)	500
Total RF power consumption (kWt)	1000

The IP parameters

Betatron functions, β_x^*/β_y^* (cm)	1/15
Dispersion function ψ_y^* (cm)	±40
Transverse beam dimensions, σ_x^*/σ_y^* (μm)	6/400
Tune shifts, ξ_x/ξ_y	0.05/0.01
Collision energy spread, σ_W (keV)	<100
Luminosity L per IP, (cm^{-2}s^{-1})	$1.5\cdot10^{33}$

A number of interesting experiments will be carried out at the J/ψ-meson energy, W = 3.1 GeV. Due to its narrow width Γ = 70 keV, monochromatization is particularly important for these experiments. Taking into account vertical emittance enhancement by the intra-beam scattering which reduces monochromatization, the τcF main parameters at the J/ψ-meson energy look as follows:

Beam energy, Eo (GeV)	1.55
Beam current, I (mA)	400
Emittances, $\varepsilon_x/\varepsilon_y$ (nm·rad)	2.2/0.25
Tune shifts, ξ_x/ξ_y	0.05/0.007
Collision energy spread, σ_W (keV)	35
Luminosity, L (cm^{-2}, s^{-1})	$6\cdot10^{32}$

Finite crossing angle

Further development of the τcF collider may be based on introduction of a finite crossing angle into the scheme with monochromatization. The angle 2θ = 20÷50 mrad will not enhance the already existing synchro-betatron coupling significantly, but allows to raise the bunch collision frequency f_c up to 100÷200 MHz and to achieve luminosity in the range $L = 5\cdot10^{33}\div10^{34}\,\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$ at the maximum beam energy.

However, monochromaticity will be lost. If needed, it can be restored using the idea of crab-crossing[9].

Summary

The presented study has revealed some advantages of the monochromatic τcF design. The collider promises to be a low current, low emittance machine, insensitive to beam energy spread blow-up due to the microwave instability. It also possesses a good dynamic aperture owing to small transverse beam dimensions and the possibility of using sextupoles close to the final focus lenses. Finally, it should provide 35 keV centre-of-mass energy spread at the J/ψ-meson energy, which is twice smaller than the width of this resonance.

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