ANL/ASD/CP--87782
CONF-9506186--2

Argonne Tau-charm Factory Collider Design Study

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NOV 21 1995

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Abstract. The design approach and design principles for a Tau-charm Factory at Argonne were studied. These studies led to a set of preliminary parameters and tentative component features as presented in this paper.

INTRODUCTION

Since 1993 members of Argonne's High Energy Physics (HEP) division have been considering the possibility of constructing a Tau-charm Factory (TcF) on site. Delegates from HEP participated in both the 1989 and the 1994 workshops on the TcF at SLAC. An evaluation of the physics case (1) for the facility was performed by an *ad hoc* committee formed in October 1993 within the HEP Division. The committee recommended a serious consideration of a TcF for the future plans of the division.

In addition, a small number of interested accelerator physicists from Argonne's HEP and Advanced Photon Source (APS) divisions have devoted part-time effort to the study of the design of a TcF collider. First proposed in 1987 (2), the TcF was the subject of four international workshops (3). Given the large amount of detailed studies already performed by other groups (4) and the rather demanding specification on the performance, the design options for the TcF collider are tightly confined. No great departures from the "standard" design seem worth consideration. A re-examination remains to be done with a possible redirection of the style and the principle adopted for the design, and potentially different engineering choices. For the latter we have leaned heavily on our up-to-date experiences derived from the APS project.

We adopted the following starting principles in our design study:

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1. The phased approach—This is based both on economic and operational considerations. The complexity and precision requirements of the machine are such that operational experiences at one stage will greatly enhance the probability of success in the construction and operation of the succeeding, more sophisticated phases.
2. Simplicity of the design—The design should be as simple as possible while satisfying the following demanding specifications: a) the total center-of-mass energy is adjustable from 3 to 6 GeV, b) the luminosity is greater than $10^{33}/\text{cm}^2/\text{s}$ over the entire energy range, c) the energy spread at 3.1 GeV is within the width of the J/ψ , and d) collisions of longitudinally polarized (pure helicity state) beams are possible.

First we shall describe briefly our concept of the different phases of construction and operation. Then we shall describe the design of the more difficult and unconventional component systems of the collider.

PHASE I: ZERO-DISPERSION INTERACTION

As the initial phase we shall consider a single-ring collider which satisfies the energy and luminosity requirements a) and b) but not necessarily the others. The adjusted gross beam parameters are

$$\begin{aligned}\text{Emittance} &= \varepsilon \cong 560 \text{ nm-rad}, \\ \text{Energy spread} &= \sigma_E/E < 4 \times 10^{-4}.\end{aligned}$$

To equalize the horizontal (x) and the vertical (y) beam-beam limits, we set at the Interaction Point (IP):

$$\begin{aligned}\beta_x^* &= 0.06 \text{ m}, & \beta_y^* &= 0.01 \text{ m} \\ \text{and } \varepsilon_x &= 480 \text{ nm-rad}, & \varepsilon_y &= 80 \text{ nm-rad} \quad (\text{coupling} = 1/6).\end{aligned}$$

This results in beam widths

$$\sigma_x^* = 0.17 \text{ mm}, \quad \sigma_y^* = 0.028 \text{ mm}.$$

For head-on collisions of beam bunches with 1.5×10^{11} particles/bunch the beam-beam limits at a beam energy of $E = 1.55 \text{ GeV}$ are then $\xi_x = \xi_y \cong 0.04$. With a bunch spacing of 10 m (current $I = 0.72 \text{ A}$) dictated by the minimum distance needed to separate the beams, we get the luminosity $1.14 \times 10^{33}/\text{cm}^2/\text{s}$, satisfying the specification b).

The ring is composed of two Arcs and two long Straight Sections. The Arcs are composed of FODO cells with horizontal dispersion suppressors at both ends. Away from the single IP situated at the midpoint of the Interaction Straight the

beams are separated by electrostatic (ES) separators using the "pretzel" geometry. The maximum beam width outside of the Interaction Straight is $\sigma \cong 3$ mm. Thus, a ring aperture diameter of $\cong 80$ mm is adequate. More details of this arrangement will be discussed later.

PHASE II: HIGH-ENERGY RESOLUTION

The conventional scheme to reduce the center-of-mass energy spread is to impart to the colliding beams large equal and opposite vertical dispersions at the IP. This necessitates storing the beams in separate rings (see Fig. 1). The beams are brought together vertically by septum magnets and ES separators (combiners) to collide head-on. The orbit functions at the IP are adjusted to

$$\begin{aligned}\beta_x^* &= 0.01 \text{ m}, & \beta_y^* &= 0.076 \text{ m}, \\ D_x^* &= 0, & D_y^* &= \pm 0.4 \text{ m}.\end{aligned}$$

With beam emittances $\epsilon_x = 68.32$ nm-rad, $\epsilon_y = 1.63$ nm-rad and a beam intensity of 1.6×10^{11} particles/bunch (0.76 A at 10-m bunch spacing), the luminosity reaches $1.16 \times 10^{33}/\text{cm}^2/\text{s}$ at the beam-beam limit $\xi_x = \xi_y = 0.04$. The phase I ring can be retained to be used for one beam, and an identical second ring is built for the other beam. The emittance change between the two phases can be accomplished simply by changing the partition number J_x using Robinson wigglers (see below).

With finite dispersion at the IP the beam-beam force excites coupled synchrotron oscillations. Indeed, numerical simulations show broadenings of the betatron resonances due to synchrotron satellites. The effect on the beam-beam limit, however, is not clear (5). Even the zero-dispersion, hence no synchrotron coupling, beam-beam limit of $\xi \cong 0.04$ is derived only from operational experience and not from theory or simulation. We will pursue the study of this effect in the future, but for the present study we will keep the vertical beam-beam limit at $\xi_y = 0.04$. If compelling arguments are made to change the beam-beam limit we will readjust the ring parameters accordingly.

We designed the Arcs to yield an emittance at $J_x = 1$ of $\epsilon \cong 121$ nm-rad. For phase I, four Robinson wigglers with positive gradients are placed in the four straight FODO cells at the ends of the two Arcs forming the dispersion suppressors. They reduce J_x to 0.216, thereby raising the emittance to 560 nm-rad. For phase II, each rectangular Robinson wiggler magnet is rotated 180° about a central vertical axis to produce a negative gradient which leads to $J_x = 1.73$ and a corresponding emittance of 70 nm-rad. We have made rough designs of the Robinson wiggler magnet to ensure that it can be manufactured easily and operated reliably.

After phase II is implemented, there will be no need to go back to the zero-dispersion operation of phase I. The excellent energy spread and the vertical spreading of the event vertices are presumably advantageous or acceptable for all experiments at all energies. Indeed, one may consider skipping phase I altogether. In this case, one can reduce the ring aperture somewhat, since only a single beam will ever be stored in one ring. The use of Robinson wigglers and more detailed parameters for phases I and II are given in Table 1.

TABLE 1: Beam and Performance Parameters for Phases I and II

	Phase I (Zero Dispersion)	Phase II (High Resolution)
Number of rings	1	2
Dispersion at IP	$D_x = D_x' = 0$ $D_y = D_y' = 0$	$D_x = D_x' = D_y' = 0$ $D_y = \pm 0.4 \text{ m}$
Without Robinson Wiggler		
Total emittance	$\varepsilon = 121 \text{ nm-rad}$	$\varepsilon = 121 \text{ nm-rad}$
Energy spread	$\sigma_E/E = 0.4 \times 10^{-3}$	$\sigma_E/E = 0.4 \times 10^{-3}$
With Robinson Wiggler		
Wiggler bend radius	$\rho = 10 \text{ m}$	$\rho = 10 \text{ m}$
Wiggler gradient	$B'/B = 4.30 \text{ m}^{-1}$	$B'/B = -4.30 \text{ m}^{-1}$
Total emittance	$\varepsilon = 560 \text{ nm-rad}$	$\varepsilon = 70 \text{ nm-rad}$
x and y emittances		
y/x Coupling	$C = 16.7\%$	$C = 1.6\%$
Horizontal ε	$\varepsilon_x = 480 \text{ nm-rad}$	$\varepsilon_x = 68.32 \text{ nm-rad}$
Vertical ε	$\varepsilon_y = 80 \text{ nm-rad}$	$\varepsilon_y = 1.63 \text{ nm-rad}$
Energy spread in beam	$\sigma_E/E = 0.33 \times 10^{-3}$	$\sigma_E/E = 0.49 \times 10^{-3}$
Amplitude function at IP	$\beta_x = 0.06 \text{ m}$ $\beta_y = 0.01 \text{ m}$	$\beta_x = 0.01 \text{ m}$ $\beta_y = 0.076 \text{ m}$
Center-of-mass energy spread		
at $2E = 3.1 \text{ GeV}$ (for J/ψ)	$2\sigma_{E0} = 1.03 \text{ MeV}$	$2\sigma_{E0} = 0.086 \text{ MeV}$
No. of particles per bunch	$N = 1.5 \times 10^{11}$	$N = 1.6 \times 10^{11}$
Beam-beam parameter	$\xi_x \cong \xi_y \cong 0.04$	$\xi_x \cong \xi_y \cong 0.04$
Bunch spacing	10 m	10 m
Beam current	0.72 A	0.76 A
Luminosity (head-on collision)	$1.14 \times 10^{33}/\text{cm}^2/\text{s}$	$1.16 \times 10^{33}/\text{cm}^2/\text{s}$

Straight-section Matching

The requirements of orbit-function matching in the straight sections are the same for phases I and II. In the Utility Straight the matching depends on the detailed geometrical arrangement of the injection lines and elements, the rf cavities, the beam scrapers and aborts, etc. Since detailed geometrical arrangements cannot be finalized at this time, and since the matching is relatively straightforward, no effort has been spent on designing this section.

In the Interaction Straight the matching consists mainly of producing the orbit separation of the two beams and matching the orbit functions at the end of the Arc to those desired at the IP. We have performed many matching exercises with various assumed matching conditions just to assure that the assumed geometry and transport elements provide adequate flexibility to take care of all requirements. To form the orbit separation, moving away from the IP we first have a strong superconducting quadrupole doublet used commonly by both beams to produce the mini- β values at the IP. For phase I, the beams are then separated into the "pretzel" geometry by two sets of ES separators, one vertical and one horizontal, spaced by $\sim 90^\circ$ betatron phase advance. For a bunch spacing of 10 m, the next bunch crossing point is 5 m away from the IP. At that point the beams are already separated by more than 12 rms width so that the electromagnetic interaction between them is tolerable. The mini- β quadrupole doublet and the "pretzel" forming ES separators can all be accommodated in a straight section space of ~ 25 m. However, since the β -function matching requires a longer distance, a length of about 60 m is allocated on either side of the IP. Neglecting the rather small dispersion introduced by the ES separators, both the horizontal and the vertical dispersions remain essentially zero throughout the straight section.

For phase II with two vertically separated rings, after the first set of vertical ES separators a 5-m drift space increases the beam separation to a value sufficiently large to clear the septum of a center-septum magnet with equal and opposite fields on opposite sides. After the septum magnet, the beams go into separate transport lines having the same optics and opposite vertical geometry and dispersions. In addition to the minimum dog-leg, extra vertical bends are added to provide more flexibility in the matching. Many studies and sample matchings were performed. A typical example of a matched geometry and orbit functions are shown in Figs. 2 and 3. In Fig. 3 the values $\beta_x = 10.0$ m, $\beta_y = 4.0$ m, $D_x = D_y = 0$ at the end of the Arc are matched to the specified values $\beta_x^* = 0.01$ m, $\beta_y^* = 0.076$ m, $D_x^* = 0$, $D_y^* = \pm 0.4$ m at the IP.

In general for colliders with mini- β IPs, the maximum β values inside the common quadrupole doublet are so large that the large chromaticities generated by these quadrupoles must be corrected by sextupoles placed close by, in order that the

dynamic aperture limitations imposed by the sextupoles are not overly restrictive. When matching the Interaction Straight we strive to keep the maximum β values in the mini- β quadrupoles as low as possible taking advantage of the additional flexibility introduced. This allows the chromaticity corrections to be provided by sextupoles distributed only in the Arcs next to the cell quadrupoles. The dynamic apertures remain ample over the entire energy spread in the beam, as shown in Fig. 4. Not having to correct the chromaticities immediately next to the mini- β quadrupoles greatly simplifies the Interaction Straight matching and the matching transport elements.

We also looked into approximate first-order designs for all the transport elements—superconducting mini- β quadrupoles, ES separators, septum vertical dipoles, etc.—to make sure that these transport elements can be fabricated with available material and technology and operated with the required performance and reliability.

Beyond phases I and II we visualize two further phases, although we have not been able so far to spend any effort on their design.

PHASE III: SUPER-HIGH LUMINOSITY

To further increase the luminosity by, say, a factor of 3, one can reduce the bunch spacing by a factor of 3 to some 3 m, and make the beams cross at a finite angle so that they are naturally separated at the next crossing point 1.5 m away from the IP. In this case, to reap the full luminosity gain of a factor of 3, the beam bunches must be canted to form the "crab-crossing" geometry. This geometry has been extensively studied (6) and can presumably be adopted rather straightforwardly. However, more detailed efforts are needed to investigate the possibility of incorporating the large vertical dispersions in the "crab-crossing" geometry to reduce the center-of-mass energy spread. If the reduced energy spread arrangement is incompatible with this geometry, the capability of going back to phase II for charmonium production should be retained.

PHASE IV: POLARIZED BEAMS

To study symmetry-violating reactions (7), collisions of longitudinally polarized particles are desired. The possibility of providing polarized beam collisions has been studied in some detail by A. Zholents (8). In this scheme the beams are first transversely polarized by the Sokolov-Ternov mechanism in a storage ring with very strong bending fields, hence very small radius. The typical polarization time is some tens of minutes. Spin rotators are added to the TcF ring

so that the eigen-spin direction at the IP becomes longitudinal while the eigen-spin direction at the injection point remains transverse. The injected transversely-polarized beam will then collide in pure helicity states. We intend to pursue the design of this phase in detail in the near future. To provide the additions and modifications necessary for implementing this phase will be difficult and costly. In any case, even after phase IV is implemented one should retain the capability of colliding unpolarized beams.

Beyond the overall beam design and the approximate design of the ring transport elements, we also investigated the design of other component systems of the ring. For all these we draw heavily on our up-to-date experience with the corresponding components in the Advanced Photon Source.

COMPONENT SYSTEMS

Vacuum System

Extruded aluminum chambers with button-type beam position monitors (BPM) mounted directly on the chambers have performed very well in the past. Aluminum is easy to extrude and has good thermal conductivity; thereby it is easy to cool and has a low gas desorption coefficient ($\eta_\gamma = 2 \times 10^{-7}$ mol./photon after 150 Ampere-hour of synchrotron radiation cleaning) and a low bake-out temperature ($< 200^\circ\text{C}$). The aluminum-to-stainless steel transition is by now a well-known and reliable technology. Distributed pumping is best provided by non-evaporative getter (NeG) pumping strips. The Zr/V/Fe NeG strip has a pumping speed of 300 liter/s for a 100 cm² surface area. These strips are mounted over the circumference of the entire ring on the inner-radius side of the vacuum chamber and separated from the main beam chamber by a wall with pump-out slots. With flush-mounted BPM buttons and with all chamber discontinuities, protrusions, and irregularities carefully shielded, one should be able to keep the coupling impedance low enough to avoid single bunch instabilities in the beam at the required high currents. Lumped ion or getter pumps are added at locations with high outgassing rates, such as the rf cavities.

RF System

The highest frequency should be used to give the shortest beam bunch. To realize the maximum luminosity the bunches should not be much longer than the smallest β at the IP, namely, ~ 1 cm. The highest frequency cw klystron available operates at 500 MHz. At this frequency, to achieve a 1-cm short bunch length, one needs a rather high rf voltage, some 4 MV. Operating close to the transition energy

would be useful. However, this requires a lattice with very high transition energy which can be adjusted over the operating beam energy range of 1.5 GeV to 3.0 GeV. This is obviously difficult to achieve. Furthermore, at the very high bunch current discussed, a great deal of bunch lengthening can be expected. Clearly some further thinking and new ideas are needed.

Single cavities are likely to have the fewest higher-order modes (HOMs). These HOMs must be deQed so as not to excite the bunch-to-bunch instabilities in the beam. In case the deQing of the HOMs alone is not adequate to stabilize all coupled bunch modes, the beam can be stabilized by the use of properly designed feedback systems. Recent developments suggest that for cw operation at this frequency and voltage, superconducting cavities would be more advantageous.

Magnet Power Supplies

All horizontal Arc dipoles are connected in series and powered by a 12-phase rectifier power supply. The vertical dipoles in the Interaction Straight are individually powered and controlled. Furthermore, it is convenient to have all the ring quadrupoles, sextupoles, and orbit-corrector dipoles individually powered and individually adjustable. The "chopper" type of d.c. supplies as used on the APS and other synchrotron radiation rings is convenient, reliable, and available at reasonable cost.

CONCLUSION

The rather demanding performance requirements for the TcF almost uniquely defines the configuration of the machine. The Argonne design study incorporated only minor departures and shifts in emphasis from the "standard" design. The study offered a review and critique of the design rationale and features. It is understood that substantially more effort is needed to reach the level of a realistic Conceptual Design Report.

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FIGURE 1. Overall geometry of the two collider rings for Phase II. The extra vertical bends in the Interaction Straight are introduced to provide flexibility.

FIGURE 2. The vertical geometry of the orbits of the colliding beams in Phase II. The orbit-separating elements are: ES = electrostatic separator; BS = septum dipole; B1, B2, B3, B4, B5 = separate dipoles on separated beams (shown as singles).

FIGURE 3. Orbit functions over a quarter of the ring. The Interaction Straight matching quadrupoles Q1 to Q11 are as shown in Fig. 2. The Arc elements are: cell dipoles BC; cell quadrupoles QF, QD; and Robinson wigglers RW. Not shown are the sextupoles.

FIGURE 4. Dynamic apertures at various energy deviations for the lattice shown in Fig. 3.

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