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ФИЗИКА И ТЕХНИКА УСКОРИТЕЛЕЙ

THE PROJECT OF TAU-CHARM FACTORY WITH CRAB WAIST IN NOVOSIBIRSK

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The project of a new-generation tau-charm factory is now under consideration in Novosibirsk. A novel approach of the Crab Waist collision scheme allows reaching the luminosity of $(1{-}2)\cdot 10^{35}$ cm$^{-2}\cdot$s^{-1}. The other features of the facility are: variable energy from 3 to 4.5 GeV (c.m.), electron beam polarization, flexible usage of damping and excitation wigglers to keep high luminosity for all energy levels, etc. We discuss some of the challenges and opportunities available with the development of the project.

В настоящее время в ИЯФ им. Г. И. Будкера (Новосибирск) рассматривается проект нового поколения tau-charm-фабрики. Использование современной схемы встречи пучков — Crab Waist — позволяет достичь максимальной светимости $(1{-}2)\cdot 10^{35}$ см$^{-2}\cdot$с$^{-1}$. К другим характеристикам установки относятся: энергия, изменяемая в диапазоне от 3 до 4,5 ГэВ (в с. ц. м.), продольная поляризация электронного пучка в месте встречи, возможность гибкого регулирования размеров пучков для получения максимальной светимости при всех энергиях и т. д. Обсуждаются особенности создания фабрики.

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INTRODUCTION

A tau-charm factory (TCF) can address the issues concerning the tau leptons, charmed particles, and light quark spectroscopy in a unique manner. Many of these issues can only be addressed by a tau-charm factory and may not be substituted by the successfully operating B-factories. A number of different projects of TCF were discussed in the '90s of the last century [1–6]. All these projects had more or less similar features: the maximum luminosity around 10^{33} cm$^{-2}\cdot$s^{-1} and the single beam energy variable in the range $\sim 1{-}3$ GeV.

One of the representatives of this family, the Beijing Tau-Charm Factory, is now at the final stage of construction and the first beams collision is expected in the fall of 2007.

In 1995 BINP also released a conceptual design of tau-charm factory [7] with the following characteristics:

- Beam energy in the range 0.7–2.5 GeV.
- Round beam mode luminosity is 10^{34} cm$^{-2}\cdot$s^{-1}.
- Luminosity in the monochromatization mode is 10^{32} cm$^{-2}\cdot$s^{-1}.
- Longitudinal polarization of the electron beam.
- Transverse beam polarization for precise energy calibration.

In the framework of the BINP TCF project a new e^+e^- injection facility has been started. An excavation work of the TCF main halls and tunnels has been started in 1996 but then it was frozen. However, recently we decided to revive the TCF project in Novosibirsk and this time our optimism was inspired by the following issues:

• The improvement of economy situation in Russia.

• Invention of the Crab Waist collision concept that allows (at least theoretically) one to increase the luminosity by factor of 10–100.

• Exciting results from the B-factories, which enhance significantly an interest to the physics of charmed particles.

The following task list was formulated for the new TCF project:

• D–$\overline{D}$ mixing.

• CP violation search in charm decays.

• Study of rare and forbidden charm decays.

• Standard Model tests in tau–lepton decays.

• Searching for lepton flavor violation.

• CP/T violation search in tau–lepton decays.

This experimental program can be carried out at a facility with the basic features listed below:

• Collision energy variable from 3 to 4.5 GeV (from J/ψ to charm baryons).

• The luminosity $\geqslant 10^{35}$ cm$^{-2}\cdot$ s^{-1}.

• At least one beam (e^-) should be polarized longitudinally.

• No energy asymmetry is needed.

• No beam monochromatization is needed.

• An accuracy of energy calibration $\sim (5{-}10) \cdot 10^{-4}$ can be easily achieved with the Compton backscattering technique already realized at VEPP-4M [8], so the transverse polarization of the beam is now not needed.

Other constraints include relevance of the new factory performance to the capability of the injection facility, which is now entering the commissioning stage and matching of underground tunnels and halls, which have been already constructed for the previous TCF design.

CRAB WAIST COLLISION SCHEME

One of the key requirements of high luminosity colliders is extremely small β_y at IP. Namely, β_y cannot be made much smaller than the bunch length without incurring in a «hourglass» effect, so this imposes a rigid limitation on the bunch length. But, unfortunately, it is very difficult to shorten the bunch length σ_z in a high current ring without incurring in instabilities.

This problem can be overcome with the recently proposed Crab Waist collision scheme [9], which can substantially increase luminosity without having to decrease the bunch length, since it combines several potentially advantageous ideas. The first idea is the use of a large Piwinski angle

$$\phi = \frac{\sigma_z}{\sigma_x} \tan\frac{\theta}{2} \approx \frac{\sigma_z}{\sigma_x}\frac{\theta}{2},$$

where θ is the horizontal crossing angle; σ_z and σ_x are the rms bunch length and the horizontal beam size.

For collisions at a crossing angle ϕ the luminosity L and the horizontal ξ_x and the vertical ξ_y tune shifts scale as [10]:

$$L \propto \frac{N\xi_y}{\beta_y} \propto \frac{1}{\sqrt{\beta_y}}, \quad \xi_y \propto \frac{N\beta_y}{\sigma_x \sigma_y \sqrt{1+\phi^2}} \propto \sqrt{\beta_y} \text{ and } \xi_x \propto \frac{N}{\varepsilon_x (1+\phi^2)},$$

where N is the number of particles per bunch; ε_x is the horizontal emittance and σ_y is the vertical rms beam size at IP. We consider here the case of flat beams, small horizontal angle $\theta \ll 1$ and large Piwinski angle $\phi \gg 1$.

In the Crab Waist collision scheme, the Piwinski angle is increased by decreasing the horizontal beam size and increasing the crossing angle. In this way, the luminosity is increased, and the horizontal tune shift due to the crossing angle decreases.

The most important effect is that the overlap area of colliding bunches is reduced, as it is proportional to σ_z/θ and β_y can be made comparable to the overlap area size (i.e., much smaller than the bunch length):

$$\beta_y \approx \frac{\sigma_x}{\theta} \ll \sigma_z.$$

A smaller spot size at IP and a reduction of the vertical tune shift can be achieved at the same time, providing an increase in luminosity inversely proportional to β_y.

The main advantage in such a collision scheme is that the bunch length must not be shortened to increase the luminosity. This will certainly ease the problems of HOM heating, coherent synchrotron radiation of short bunches, excessive power consumption, etc.

However, a large Piwinski angle itself introduces new beam–beam resonances and may limit the maximum achievable tune shifts (see, for example, [10, 11]). This is where the Crab Waist innovation is required. The Crab Waist transformation boosts the luminosity, mainly by suppression of betatron (and synchrobetatron) resonances that usually arise through the vertical motion modulation by horizontal beam oscillations [13]. In this scheme the modulation becomes significantly smaller as compared to the head-on collision scheme, thus the beam–beam limit ξ_y increases by a factor of about 2–3.

A sketch of the Crab Waist scheme is shown in Fig. 1.

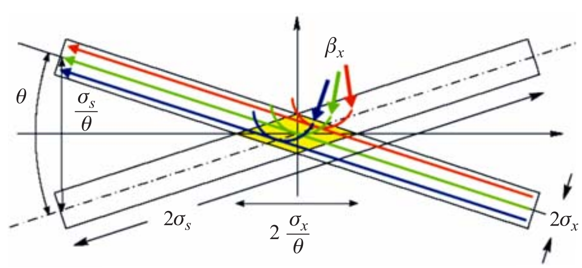

Fig. 1. Sketch of large Piwinski angle and Crab Waist scheme. The collision area is shown in yellow

The Crab Waist correction scheme is realized in practice with two sextupoles magnets in phase with IP in the x plane and at $\pi/2$ in the y plane, on both sides of IP, as shown in Fig. 2. The position of such sextupoles in the ring lattice has to be studied with great care, minimizing nonlinearities that may induce a reduction of the ring dynamic aperture.

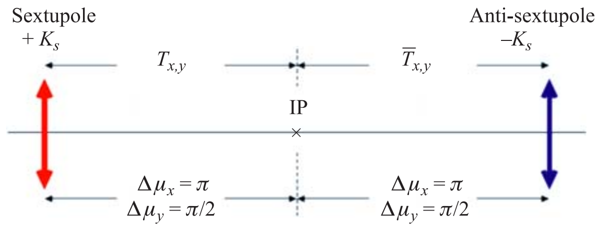

Fig. 2. Scheme of Crab Waist correction by sextupoles

The Crab Waist concept is popular now for considering new colliding facilities all over the world. A mention can be made of Super B-factory in Italy [14], Super KEKB project [15], Super B-factory at Fermilab [16]. A concept itself is planned to be proved experimentally at DAΦNE in Italy this year [17].

PHYSICS CHALLENGES

A schematic view of the TCF layout is shown in Fig. 3. A two-ring configuration with the racetrack rings, single collision point and a system of the emittance damping and excitation wigglers is considered. A circumference of the machine is around 700 m, a straight section length is ~ 100 m and the arcs radius is ~ 90 m. In design of the injection complex we use the already existing facilities and engineering infrastructures.

The design of a high-luminosity TCF leads to physics challenges primarily in the areas of lattice design, IR design, dynamic aperture optimization and the beam–beam interaction.

Luminosity. The peak luminosity has been optimized for the beam energy of 2 GeV. To reach the goal of $\geqslant 1{\cdot}10^{35}$ cm$^{-2}\cdot$ s^{-1} the following essential parameters of the colliding beams should be met: small emittance $\varepsilon_x = 10$ nm $\cdot$ rad, small betas at IP $\beta_x/\beta_y = 23$ mm/0.75 mm,

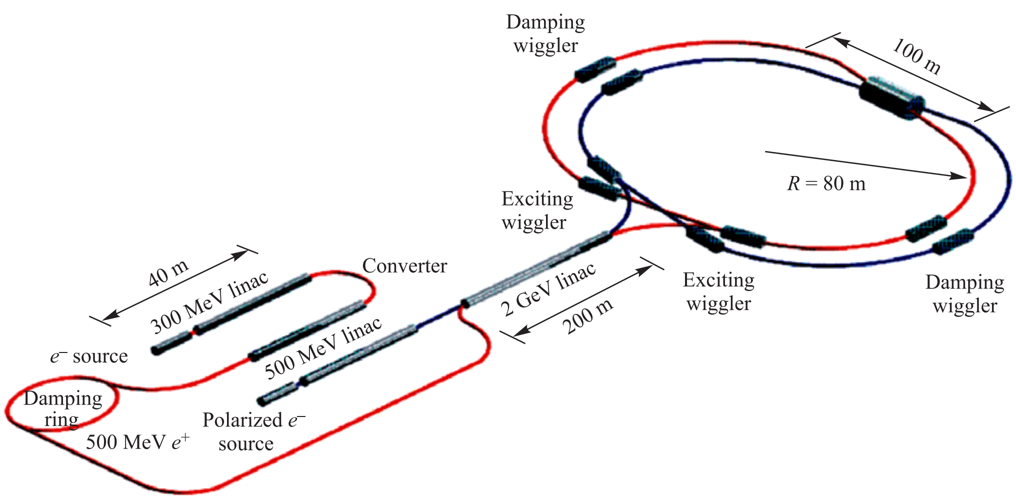

Fig. 3. Schematic view of the Novosibirsk TCF

large crossing angle at IP $2\phi_x = 40$ mrad, long bunch length $\sigma_s = 10$ mm and Crab Waist optics including the pair of strong sextupoles around IP with proper phase advance to IP. Table 1 lists the main machine parameters and the TCF luminosity at three energy levels.

Table 1. **Main parameters of the Novosibirsk TCF**

Energy, GeV	1.5	2.0	2.5
Hor. emittance, nm	10		
Coupling, %	1		
Bunch length, mm	10		
Bunch number	514		
Particles/bunch	$5 \cdot 10^{10}$	$6.5 \cdot 10^{10}$	$8 \cdot 10^{10}$
Particles total	$2.6 \cdot 10^{13}$	$3.6 \cdot 10^{13}$	$4.1 \cdot 10^{13}$
Bunch current, mA	3.1	4.3	5.0
Total current, A	1.6	2.2	2.5
Energy loss/turn, keV	260	340	430
Power loss, kW	410	750	1100
Damping times, ms	30/30/15		
Betas at IP, mm	23/0.75		
Crossing angle	40		
Parameter ξ_y	0.1		
Luminosity, $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$	$7 \cdot 10^{34}$	$1.3 \cdot 10^{35}$	$1.8 \cdot 10^{35}$

It is worth mentioning that neither of the above parameters seem to be too excessive: even smaller emittance is typical of the latest generation synchrotron light sources; the total current of ~ 2 A was obtained in PEP II and DAΦNE; a few millimeter vertical beta, $\xi_y = 0.1$ or 10 mm bunch length can be attributed to KEKB. No doubts reaching all these figures is a challenge but all accelerator technologies required for that already exist.

A sophisticated tracking of the beam–beam collision without and with the Crab Waist conditions by a LIFETRACK computer code [18] has shown an advantage of the last one.

At the luminosity scan presented in Fig. 4 a suppression of betatron coupling resonances with the Crab Waist optics is clearly seen. As a result, the betatron tune region available for high luminosity is opened substantially.

Lattice Design. Both rings of the TCF have the same racetrack design with two arcs ($\sim$ 280 m each) and two long straight sections ($\sim$ 100 m). The facility circumference ($\sim$ 760 m) is constrained by the tunnel that is now under construction at BINP. The lattice can be separated into the following sections: two arcs, producing the required emittance; IR with the Crab Waist optics; a long straight section opposite to IR and intended to accommodate RF, injection and other technological equipment; several straights for wigglers to control the emittance with energy change and matching cells between all mentioned parts.

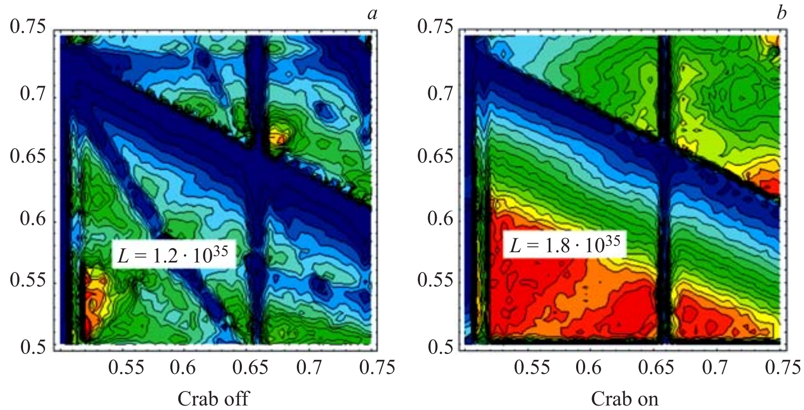

Fig. 4. A luminosity scan by LIFETRACK. Axes are the betatron tunes. The red color corresponds to the highest luminosity while the blue is the lowest one

Key parts are the arcs producing the low emittance and the interaction region with the final focus and the Crab sextupoles.

Different cells (FODO, DBA, TME) have been considered as the candidates for the low emittance arcs and finally a simple FODO was selected because its focusing strength is enough to get the required emittance and, at the same time, to provide compact and reliable cell with reasonable strength of chromatic sextupole.

An essential idea of the machine tuning is using a combination of 24 damping and 16 excitation wigglers to control radiation parameters and to optimize the Crab Waist luminosity parameters in the whole energy range.

The design of IR with the low beta final focus and the Crab Waist optics is a most challenging task in the TCF lattice development because the following restrictions should be kept in mind: very small spot sizes at IP; local correction for the very high chromaticity due to the highly focused beam; keeping geometric aberrations small; separation of two

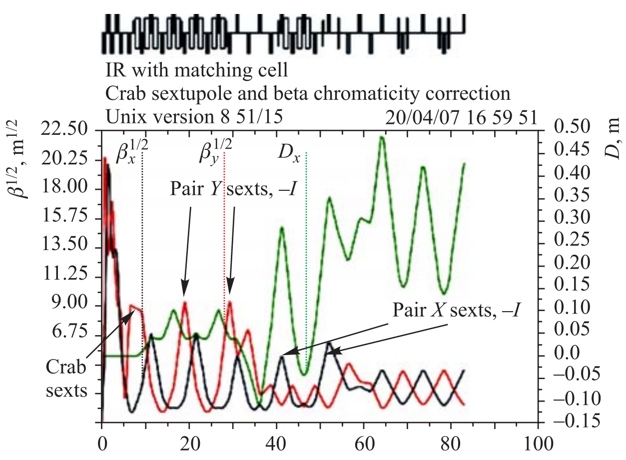

Fig. 5. TCF FF lattice functions

beams from the rings as soon as possible; preventing synchrotron radiation production from hitting the beam pipe and the detector. Presently, we have a preliminary solution based on the Raimondi–Seryi FF approach [19] with sextupole pairs spaced by $-I$ in phase and compensation of the chromatic and the geometry aberrations locally (Fig. 5). In our design a dispersion vector (η, η') is zero at IP and at the Crab sextupoles location and special dipoles introduce the dispersion to the location of the chromatic sextupoles.

Table 2 lists the main parameters of the TCF lattice.

Table 2. **Main parameters of the TCF lattice**

E, GeV	1.5	2.0	2.5
L, m	762.71		
Q_x	24.53		
Q_y	24.57		
ε_x, nm · rad	10		
σ_s, mm	10		
ξ_x	–117	–117	–117
ξ_y	–229	–231	–232
σ_E/E, 10^3	0.63	0.71	0.87
τ_x, ms	30	30	20
α, 10^3	1.02	1.13	1.21
U_0, MeV	0.25	0.34	0.79
U_{RF}, MV	0.51	0.88	1.83
Q_s, 10^3	7.9	9.7	12.8
$\Delta E/E$, %	0.76	0.95	1.12

At the moment, the TCF lattice includes 140 dipoles, 180 quadrupoles, 188 sextupoles, 16 excitation and 24 damping wigglers.

Dynamic Aperture and Beam Lifetime. Due to the very strong focusing almost 50% of the horizontal and 80% of the vertical chromaticity are induced and corrected in the FF region. It requires high strength sextupole magnets and the study shows that they, together with the Crab sextupoles, are the main source of the dynamic aperture (DA) limitation. The main problem at the moment is rather small momentum DA and a special attention is focused now to increase the stable area of particle motion.

There are two sources of the beam lifetime degradation in TCF: the Touschek effect and the loss of particles due to scattering at the interaction point at a rate proportional to the machine luminosity. At the low energy the Touschek lifetime dominates ($\sim$ 200 s) and this is one more point for a further lattice optimization.

At the high energy the beam lifetime due to the Bhabha process (radiative and elastic), that scatters particles outside the ring acceptance, and the Touschek lifetime have approximately the same value of $\sim$ 2000 s.

TECHNOLOGY CHALLENGES

Injection. To reach the specified luminosity we have to provide a top-up injection of $(2{-}4) \cdot 10^9$ particles at 50 Hz repetition frequency.

At present a new Injection Facility (IF) is commissioned at BINP. It consists of a 300 MeV electron linac, a conversion system, 510 MeV e^+e^- linac and the damping ring of the same energy (Fig. 6).

Fig. 6. Damping ring under commissioning

Today the facility produces $2 \cdot 10^{10}$ e^-/pulse yielding at the 50 Hz repetition rate and with 1.5% conversion coefficient $1.5 \cdot 10^{10}$ e^+/s. In the future we plan to use the facility to supply TCF with positrons. The following upgrade is available: new electron gun can increase the electron intensity by factor 3; more effective focusing system in the positron linac may enhance the positron current by 1.5; installation of a debuncher at the exit of the positron linac provides better matching of the beam energy spread with the energy acceptance of the damping ring and, hence, increases twice the injection efficiency. Totally the positron production capacity can be enlarged up to $1.4 \cdot 10^{11}$ e^+/s.

Experimental performance of TCF requires longitudinally polarized electrons. To deliver such electrons we plan to use a Polarized Electron Source (PES) that was developed by BINP and has operated successfully at AmPS (Netherlands) for many years [18]. The polarized electrons are accelerated to 510 MeV by the linac identical to the one of the injection facility. Finally, a 200 m long 2 GeV linac will be shared in turn between positron and electron beams to inject the particles in TCF at the energy of experiment.

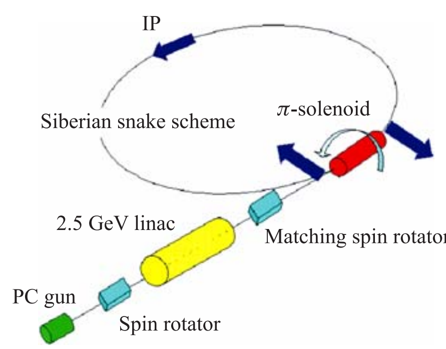

Fig. 7. TCF spin manipulation schematically

Beam Polarization. To obtain longitudinally polarized electrons at IP several options were considered. At the moment, it seems that the most appropriate way is to produce polarized electrons by PES [20] and manipulate them in TCF with the Siberian snake as it is shown in Fig. 7. The SC solenoid in the injection section turns the spin around the velocity vector by π. In IP the Siberian snake keeps the polarization vector orientation along the beam

Fig. 8. A 800 m tunnel for 2.5 GeV linac

direction. A spin precession tune is equal to 0.5 for any energy. Betatron coupling is compensated locally in the π-solenoid section by pair of skew quadrupoles.

Other options of the longitudinally polarized electrons production (for instance, using radiative self-polarization in the ring) require rather strong wigglers and have many drawbacks.

Infrastructure. One of the important constraints imposed on the new TCF project is using of the infrastructures already designed and partly constructed for the old TCF project. Besides the injection facility it includes the underground tunnel for the longitudinally polarized source and 2.5 GeV linac injector (Fig. 8) and halls for the storage rings.

CONCLUSIONS AND OUTLOOK

Tau-charm factory with $L \geqslant 10^{35}$ cm$^{-2}\cdot$ s^{-1} seems to be an extremely attractive facility for HEP experiments. The Crab Waist crossing approach allows us to obtain this luminosity without going too far beyond the present accelerator state-of-art and with already existing technology.

At BINP we have an advantage-ground to start the TCF project because the injection facility is under commissioning now, the tunnels for the linac and injection lines are ready, a lot of solutions put in the core of the project are based on existing wares and technologies.

Future plans for the project design include the FF improvement, the dynamic aperture optimization, the beam–beam study, Touschek lifetime increase, etc.

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