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

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Abstract

The project of a new-generation t-charm factory is now under consideration in Novosibirsk. A novel approach of the Crab Waist collision scheme allows reaching the luminosity of $1\div2\times10^{35}$ cm^{-2}s^{-1}. The other features of the facility are: variable energy from 2 GeV to 4.5 GeV (c.m.), longitudinal polarization of electrons at IP, usage of damping 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.

INTRODUCTION

A tau-charm factory can study the issues concerning the tau leptons, charmed particles, and light quark spectroscopy in a unique manner. Many of these issues can only be addressed to a t-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}s^{-1} and the single beam energy variable in the range ~$1\div3$ GeV. One of the representatives of this family, the Beijing Tau Charm Factory, has already started its operation.

In 1995 BINP also released a conceptual design of t-charm factory [7]. In the framework of the BINP TCF project, a new e^+e^- injection facility has been launched. An excavation work of the TCF main halls and tunnels was 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 (a) the invention of the Crab Waist collision concept that allows increasing the luminosity by factor of $10\div100$ and (b) the 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-Dbar 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
- Production of polarized anti-nucleons

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

- Collision energy from 2 GeV to 4.5 GeV (anti-nucleons – J/psi – charm barions)
- The luminosity $\geq10^{35}$ cm^{-2}s^{-1}
- Electrons polarized longitudinally at IP
- No energy asymmetry is required
- No beam monochromatization is required
- An accuracy of energy calibration ~5×10^{-4} can be achieved with the Compton back scattering technique realized at VEPP-4M [8], so the beam transverse polarization is not required.

Other constraints include the correspondence of the new factory performance with the capability of the injection facility, which is now entering the commissioning stage and matching of underground tunnels and halls 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 the IP. But β_y cannot be made much smaller than the bunch length without encountering 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 facing the instabilities.

This problem can be overcome with the recently proposed Crab Waist collision scheme [9], which can substantially increase luminosity without the bunch length decrease, 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, respectively.

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

$$L \propto \frac{N\,\xi_y}{\beta_y} \propto \frac{1}{\sqrt{\beta_y}},$$

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

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 $\theta << 1$ and large Piwinski angle $\phi >>1$.

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 grows, 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):

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

A smaller spot size at IP and 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, [11, 12]). 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.

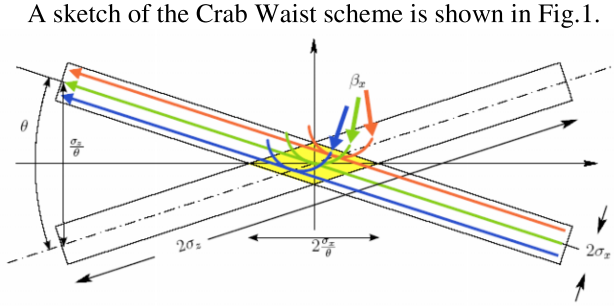

Fig.1 Sketch of large Piwinski angle and Crab Waist scheme. The collision area is shown in yellow.

The Crab Waist correction scheme is realized in practice with two sextupole magnets in phase with the IP in the x plane and at $\pi/2$ in the y plane, on both sides of the IP, as shown in Fig.2.

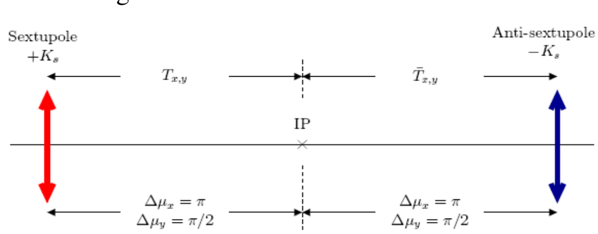

Fig.2 Scheme of Crab Waist correction by sextupoles

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.

Recently the Crab Waist concept was proven experimentally at DAΦNE in Italy [14].

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 850 m, a straight section length is ~150 m and the arcs radius is ~90 m. In the design of the injection complex we use the already existing facilities and engineering infrastructures.

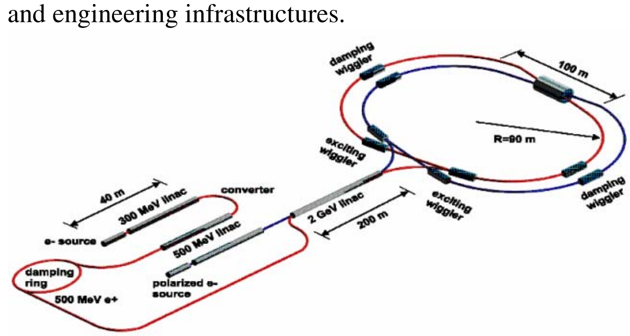

Fig. 3 Schematic view of the Novosibirsk TCF

The design of a high-luminosity TCF leads to physics challenges primarily in the areas of lattice design, IR design, e^- polarization technique, 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 $\geq 1\times10^{35}cm^{-2}s^{-1}$, the following essential parameters of the colliding beams should be met: small emittance ε_x = 10 nm-rad, small betas at IP β_x/β_y = 30 mm/0.75 mm and large crossing angle at IP $2\phi_x$ = 40 mrad.

Table 1 Main parameters of the Novosibirsk TCF

Energy, GeV	1.5	2.0	2.5
Hor. emittance, nm	10		
Coupling, %	0.5		
Bunch length, mm	10		
Bunch number	400	400	300
Particles/bunch	5.1×10^{10}	6.8×10^{10}	8.5×10^{10}
Bunch current, mA	3.1	4.0	5.0
Total current, A	1.2	1.6	1.51
Damping times, ms	30/30/15		
Betas at IP, mm	30/0.75		
Crossing angle, mrad	40		
Parameter ξ_y	0.15		
Luminosity, $cm^{-2}s^{-1}$	7.8×10^{34}	1.4×10^{35}	1.6×10^{35}

Table 1 lists the main machine parameters and the TCF luminosity at three energy levels.

It is worth mentioning that neither of the above parameters seems to be too excessive: even smaller emittance is typical for the latest generation synchrotron light sources; the total current of ~2 A was obtained in PEP II and DAΦNE; a few millimeter vertical beta, ξ_y = 0.1 or 10 mm bunch length can be attributed to KEKB. Undoubtedly, reaching all these figures is a challenge but all the 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 [15] has shown the advantage of the last one.

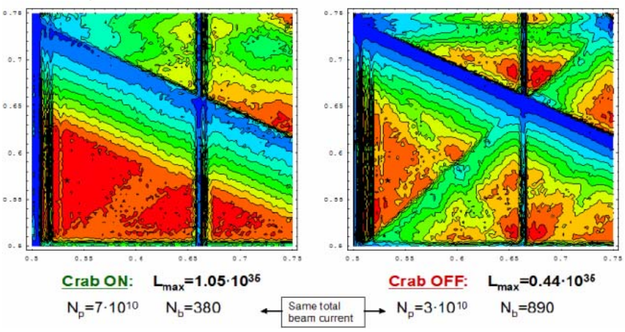

Fig. 4 Luminosity scan with the Crab-on and -off. Axes are the betatron tunes. The red color corresponds to the highest luminosity while the blue is the lowest.

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. One should note that direct comparison in Fig.4 is, to some extent, incorrect because, if we tune the Crab Waist to the maximum luminosity and switch off the sextupole, the beam-beam effects will kill the beam. That is why we had to reduce particles number per bunch and increase bunch number to plot the right diagram in Fig.4.

Lattice design

Both rings of the TCF have the same racetrack design with two arcs (~280 m each) and two long straight sections (~150 m). The facility circumference (~850 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 and sextupoles; a long straight section opposite the IR 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.

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 a reasonable strength of chromatic sextupole.

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

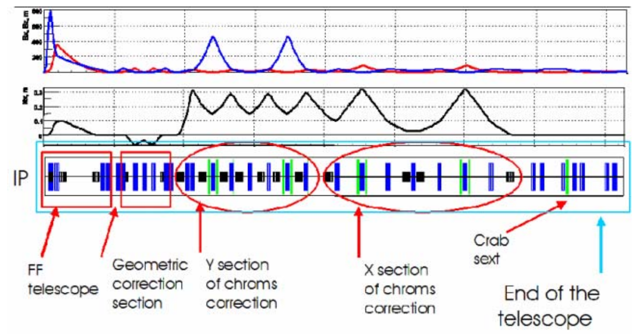

Fig.5 TCF FF lattice functions

The design of the 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 the IP; local correction for the very high chromaticity due to the highly focused beam; keeping chromatic and geometric aberrations small; separation of two beams from the rings as soon as possible; preventing synchrotron radiation production from hitting the beam pipe and the detector. Presently we have a solution based on the telescope approach 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 the IP and at the Crab sextupoles location; and special dipoles introduce the dispersion to the location of the chromatic sextupoles. Such a design provides a rather large momentum bandwidth of ±2% (Fig.6).

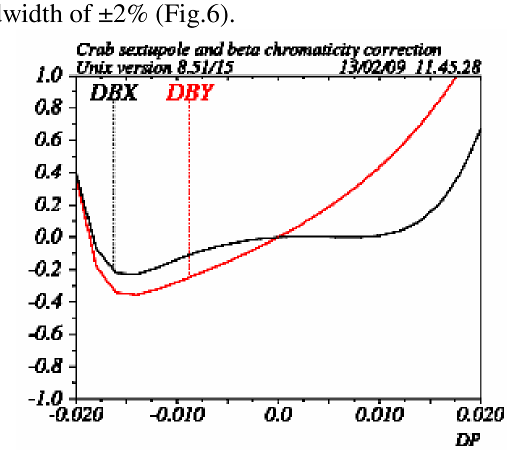

Fig.6 TCF bandwidth

Dynamic aperture and beam lifetime

Due to the very strong focusing, almost 50% of the horizontal and 80% of the vertical chromaticity is 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. A special technique of the weak DA correction sextupole pair interleaved with the strong chromatic pair was developed and provided a rather large transverse DA (Fig.7).

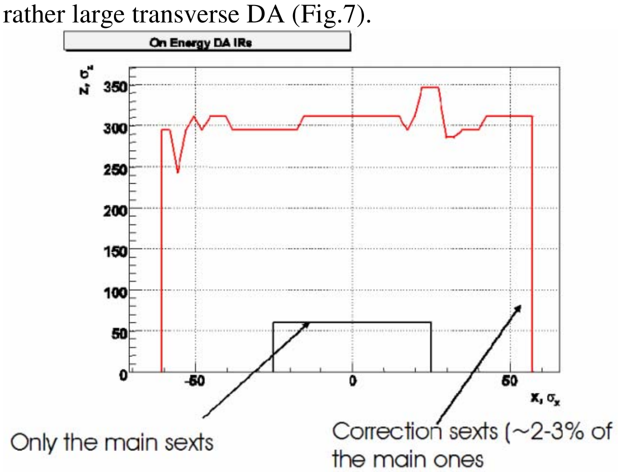

Fig.7 Correction sextupole pair opens the DA reduced by the strong chromatic sextupoles

There are two sources of the beam life time degradation in the 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 Toschek lifetime dominates (~1000 s) and this is an additional point for a further lattice optimization.

At the high energy the beam life time 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 ~2000 s.

TECHNOLOGY CHALLENGES

Injection

To reach the specified luminosity, we have to provide a top-up injection of $2 \div 4 \times 10^9$ particles at 50 Hz repetition frequency.

At present a new Injection Facility is commissioned at BINP. It consists of the 300-MeV electron linac, the conversion system, the 510-MeV e^+e^- linac and the damping ring of the same energy (Fig.8).

Today the Facility produces 2×10^{10} e^-/pulse yielding at the 50 Hz repetition rate and with 1.5% conversion coefficient 1.5×10^{10} e^+/s. In the future we plan to use the Facility to supply the 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 a better matching of the beam energy spread with the energy acceptance of the damping ring and, hence, increase twice the injection efficiency.

Fig.8 Damping ring under commissioning

Totally the positron production capacity can be enlarged up to 1.4×10^{11} e^+/s.

Experimental performance of the TCF requires longitudinally polarized electrons. To deliver such electrons we plan to use a Polarized Electron Source (PES) that was developed by BINP and operated successfully at AmPS (Netherlands) for many years [16]. 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 the experiment.

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 the PES [16] and manipulate them in the TCF with the Siberian Snakes as it is shown in Fig.9.

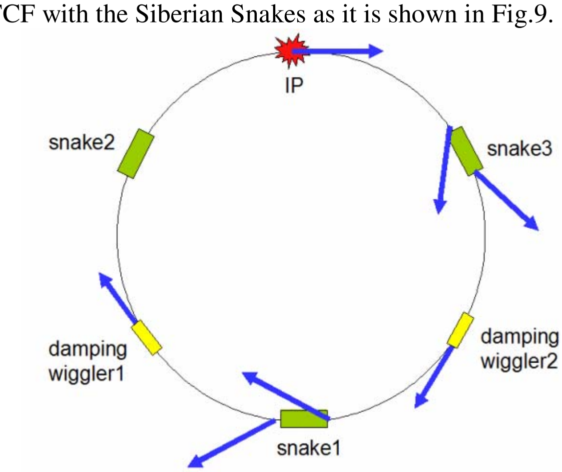

Fig.9 The odd-number Siberian Snakes spin manipulator

In our project we use 5 Snakes 12-m-long each. The Snake consists of two superconducting solenoids (L = 2.6 m, B = 5 T), rotating the spin by 90° each around the beam velocity vector, and 7 quadrupoles providing condition for the local correction of the betatron coupling.

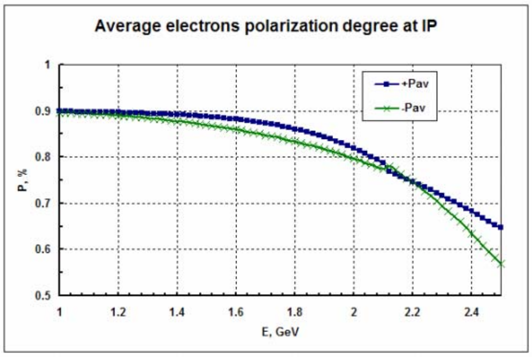

Fig.10 Average polarization degree (along and opposite the velocity vector) of the electron beam at IP vs. energy

The Snakes provide smooth (without the gaps at the spin resonance values) behavior of the average polarization degree at IP in the whole energy range. Fig.10 shows the polarization degree as a function of energy for the initial degree of 90% and the beam life time of 1000 s.

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, 2.5 GeV linac injector (Fig.11) and halls for the storage rings.

Fig.11 A 800 m tunnel for 2.5 GeV linac

CONCLUSIONS AND OUTLOOK

Tau-charm factory with $L \geq 10^{35}$ $cm^{-2}s^{-1}$ seems to be an extremely attractive facility for HEP experiments. The Crab Waist crossing approach allows us to obtain this luminosity without going far beyond the present accelerator state-of-art with the 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 the solutions put in the core of the project are based on the existing wares and technologies.

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

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