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FUTURE PROJECTS FOR THE NEXT GENERATION TAU-CHARM FACTORIES IN CHINA AND RUSSIA*

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Abstract

Based on the key scientific questions in the frontier of particle physics field, the current status and future development trend globally and domestically of accelerator-based particle physics experiments, new generation electron-positron colliders in tau-charm energy region (around 4 GeV center-of-mass) are proposed both in China and Russia. This paper discussed the general collision scheme and the key issues of accelerator physics and technologies. Also, the accelerator research and the progress of the projects in Russia and China are presented.

INTRODUCTIONS

As we know, there're two frontiers for accelerator-based particle physics. One is high energy frontier, in which scientists search for new physics beyond the standard model with very high beam energy. Meanwhile, a super particle factory usually refers to a collider which operates in the high luminosity frontier of particle physics with relatively lower energy. With a center-of-mass energy of around 4 GeV (tau-charm region), the super particle factory collider will operate in the quantum chromodynamics (QCD) perturbative and non-perturbative transition region and have unique features, such as rich resonance structures, threshold production, quantum correlation, etc, and will provide unique opportunities to study the internal structure of hadrons and explore the nature of non-perturbative QCD, to measure charge-parity (CP) violations and test the electroweak models precisely, and search for the new physics beyond-standard-model [1]. As the most successful tau charm factory of the world, the Beijing Electron Positron Collider II (BEPCII) will finish its historical mission in the next decade and certainly need a successor. Therefore, a new super tau charm factory which will have abundant physics program and great potential for scientific discoveries in high energy physics fields is required. It is expected to achieve major breakthroughs in tau-charm and hadron physics fields in future.

Both Chinese and Russian scientists have made their efforts in conceptual design study of the next generation tau charm factory and applied for funds to develop key technologies and construct test facilities since 2010s. Scientists from other countries also played an important part in related discussion. There're annual international joint workshops since the year 2018, first held in Paris, then Moscow and Hefei.

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As a next generation facility, a super tau charm factory will be a dual-ring electron-positron collider with high current symmetric and flat beams, which have very small transversal size at interaction point (IP) so as to reach 50-100 times as BEPCII's luminosity. Compared to head-on collision and large emittance beams for BEPCII, the new super tau charm factory will utilize a fundamentally new scheme called Crab Waist and large Piwinski angle [2, 3]. Although this scheme has been successfully applied in low luminosity situation by the Φ-factory DAΦNE (INFN LNF, Frascati) [4], there're still a lot of work to do if we want to achieve much higher current and luminosity in tau-charm region, especially based on SuperKEKB experience [5]. This paper discusses the key issues of accelerator physics and technologies and presented the progress of the accelerator research and the situation of the projects in China and Russia.

MAJOR CHALLENGES FOR SUPER TAU CHARM ACCELERATORS

The new approach of large Piwinski angle and Crab Waist (CW) scheme allows raising the luminosity by one or two orders of magnitude without significant increase in the intensity of the beams or the dimensions of the installation or decrease in the bunch length. The idea was first offered by P. Raimondi, M. Zobov and D. Shatilov [6], see Fig. 1.

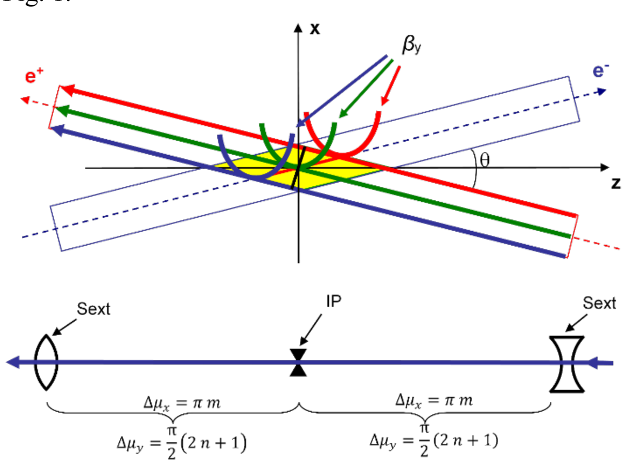

Figure 1: Large Piwinski angle and Crab Waist.

The theoretical luminosity satisfies $L = \frac{\gamma}{2er_e} \cdot \frac{I_{tot}\xi_y}{\beta_y^*} R_H$. With a Piwinski angle $\phi = \sigma_z/\sigma_x \tan(\theta/2)$ large enough, the hourglass effect will be suppressed and the bunch length doesn't have to be decreased. Crab waist sextupoles suppress the betatron and synchro-betatron resonances so the luminosity is increased [7].

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Based on experience since then, there're several major challenges for the accelerator complex.

Since the bunch current is relatively high and the bunch size is very small at IP, the collective effects will increase and the beam instability should be carefully dealt with.

Due to strong focusing in interaction region, there will be local chromatic correcting sextupoles, together with the crab sextupoles, they will introduce strong non-linearity, which will reduce the apertures.

Beam lifetime due to Bremsstrahlung is not decisive in super tau charm factories. But both the dynamic aperture and energy aperture will be smaller than they are in last generation colliders such as BEPCII, result in much shorter Touschek lifetime.

Generally speaking, the key accelerator physics and technologies involved in a super tau charm accelerator can be categorized into the following three parts:

Firstly, physics and technologies for high peak luminosity. A physical design of storage rings that can achieve high enough peak luminosity. Devices to compress the bunch in the interaction region, such as a double-aperture superconducting magnet with high precision in the interaction region, superconducting solenoids and collimators.

Secondly, technologies of advanced beam instrumentations and diagnostics to ensure the stable operation of the accelerator and adequate integrated luminosity accumulation. Such as feedback system to suppress the instabilities and increase the current limit, fast feedback at the interaction point, precision measurement (submicron) of bunch transversal size to monitor the beam blow-up, and other important beam diagnostic devices.

Last, to meet the requirements of top-up operation, the physical design and key technologies of injectors that offer high current, low emittance and high-quality electron and positron beams for the storage ring. For example, a photocathode gun with large charge, low emittance and enough repetition rate will be a good choice of electron source if we want to achieve lower injecting background and high quality positron beam.

THE SUPER TAU CHARM FACILITY IN CHINA

General Description

The Super Tau Charm Facility (STCF) has a center-of-mass energy of covering 2 to 7 GeV and a peak luminosity of 1×10^{35} cm^{-2} s^{-1} at a center-of-mass energy of 4 GeV and was firstly proposed in the year 2013. In 2018-2021, the Chinese scientists completed a preliminary physical design report. The STCF consists of an accelerator, including double storage rings of circumference approximately 800 m, a linear injector of length approximately 400 m, and a particle spectrometer. The planned STCF is estimated to have an approximate cost of 4.5 billion RMB for construction, taking approximately 10 years for technology research and development (R&D) as well as construction, and of a territory covering area one km square.

Physical Design Progress

The preliminary physical design progress was published in 2021 [8]. After that several modifications had been made. The Hybrid 7BA (H-7BA) was altered to high order achromat H-7BA to get larger dynamic aperture and momentum aperture. The tune between CCY and Final Doublet (FD) was changed, with additional sextupoles at small β position, to get large momentum aperture. A higher harmonic cavity was adopted to control the bunch length so as to adjust the beam-beam effects and get the optimum luminosity. Table 1 shows the beam parameters under further optimization.

Table 1: STCF Accelerator Parameters

Parameters	Value
Peak Luminosity	1×10^{35} cm^{-2} s^{-1}
Beam Energy	2 GeV optimized
	1-3.5 GeV tunable
Circumference	617.06 m
Current	2 A
Beam Emittance $\varepsilon_x/\varepsilon_y$ (with IBS)	4.29/0.02 nm·rad
β_x^*/β_y^*	90/0.6 mm
Crossing Angle	60 mrad
Bunch Length	10 mm with IBS
ξ_y	0.1
$\tau_{Touschek}$	200 s

Figure 2 shows the lattice function and layout of the STCF.

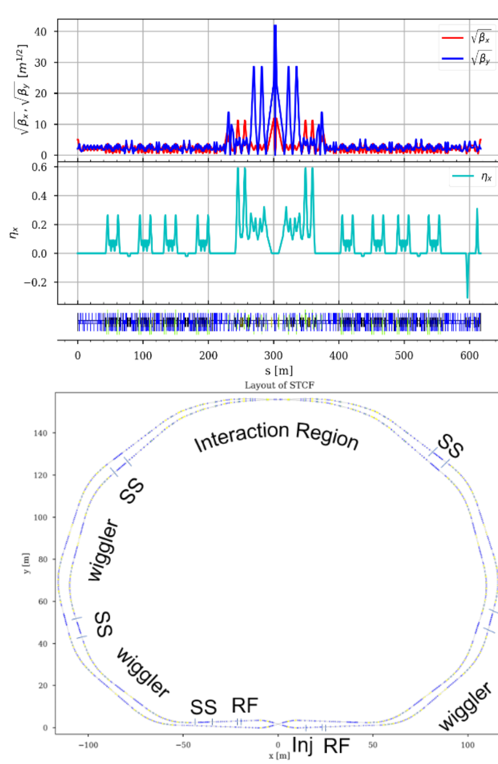

Figure 2: STCF lattice and layout.

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Figure 3 shows the dynamic aperture on and off momentum with crab sextupoles on and off. The Touschek lifetime was increased from 35s to 200s after new IR and arcs were adopted.

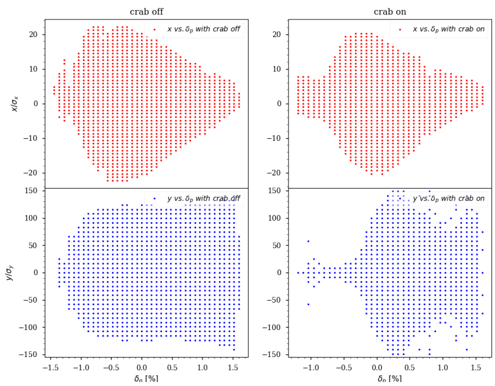

Figure 3: STCF dynamic apertures.

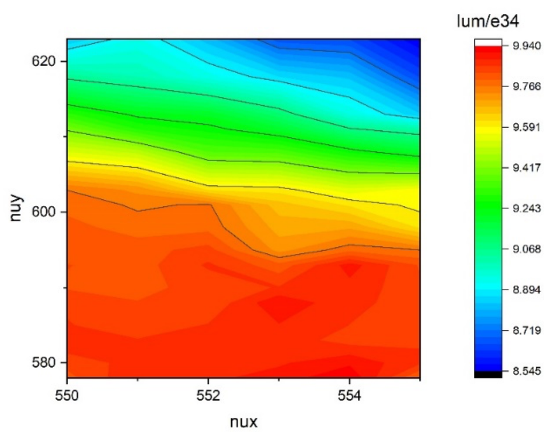

Figure 4: First STCF beam simulations results.

The preliminary beam simulation results, Fig. 4, showed that in a range of 37.550~37.555 ν_x and 27.575~27.590 ν_y a higher than 0.95×10^{35} cm^{-2} s^{-1} luminosity can be achieved after 3 times as damping time.

Future Plans

We can see that further work is still needed to get better lifetime and aperture. So, in next several years accelerator physics will be a key point. Also, three series of key techniques should be prepared.

Recently, Anhui Province is actively supporting the key technology R&D of STCF, and considering to see the STCF as part of the "Fifteenth Five Year Plan" at Hefei Comprehensive National Science Center. The full R&D and construction process will be divided into three stages: at the R&D stage (2023-2025), scientists will finish a technical design report and a test facility of high intensity injector, then apply for full support to build the whole facility. At the second stage (2026-2032) the main accelerators will be built and achieve a luminosity of about 5×10^{34} cm^{-2} s^{-1} pilot. At the third stage, after an upgrade, a luminosity of 1×10^{35} cm^{-2} s^{-1} will be achieved with the electron beam longitudinally polarized at the IP.

THE SUPER CHARM TAU FACTORY AT BINP

General Description

The Super Charm Tau Factory (SCTF) at Novosibirsk is a project of new colliding beam experiment proposed in Budker Institute of Nuclear Physics (BINP). In 2011, scientists from BINP had published their first version of CDR [9], with Machine Detector Interface (MDI) design, lattice optimization and high performance operation at all energies. In 2018, the second version of CDR had upgraded the lattice design and given more technical details [10]. From 2019 to now, the SCTF is under technical design stage, finished further optimization work, showed shorter rings, better dynamics, realistic design of MDI, lens and injection facility [11, 12]. Differs from STCF in China, SCTF will be a more ambitious project with a luminosity of 1×10^{35} cm^{-2} s^{-1} at almost all energy range and with a polarized electron beam in the first place.

Conceptual and Technical Design Progress

Figure 5 shows the lattice function and layout of the BINP STCF.

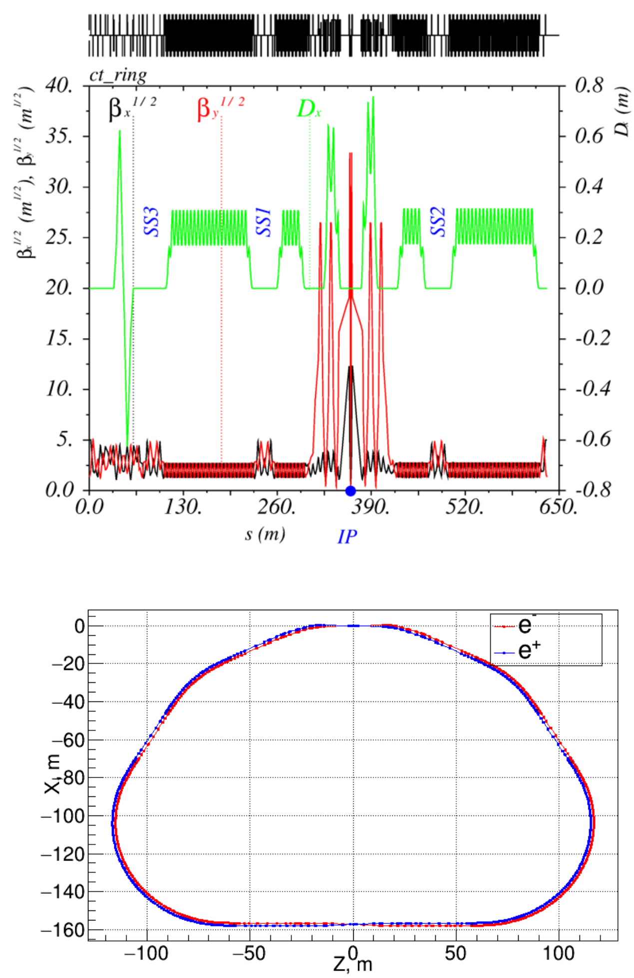

Figure 5: SCTF lattice and layout.

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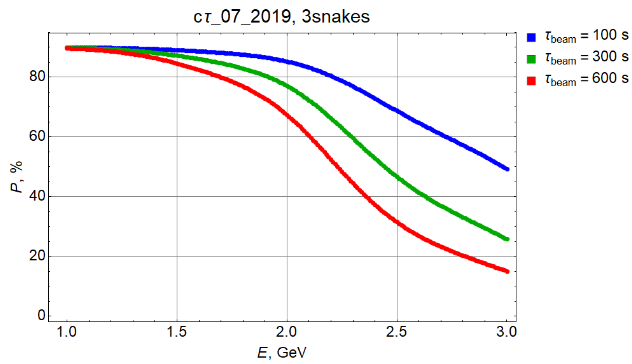

Figure 6: SCTF polarization simulation.

From Fig. 6 we can see that the linear lattice and parameters provide the desired luminosity and polarization. Recently, a realistic design of new injection facility 2×10^{11} e^+/s for 200 s of beam lifetime. The detailed design of the Interaction Region and MDI, and the 3D design of Final Focus quadrupoles are also finished, while maximum strength is reduced from 100 T/m to 40 T/m.

Future Plans

There's almost the same situation as STCF that off momentum dynamic aperture with CRAB ON is not good enough. And also, efforts in longer Touschek lifetime is always needed.

The united team with several powerful organizations, labs and institutes as supporters keeps steadily pushing the Russian government to approve the project. In spite the whole budget is still under discussion by Russian government, there was a decision to start with R&D and prototypes and money were allocated for 2022-2023 for key components. SuperKEKB experience show that there are still problems with implementation of the CW collision in real life. Therefore, to reduce risks for large super charm-tau, BINP is considering a test facility in the range of 1-1.5 GeV beam energy with all main CW features (large Piwinski angle, small emittance, large current, low βy, complicated IR, etc.).

CONCLUSION

Based on the research results from China and Russia, we can see that a super tau charm factory reaches a luminosity of 1×1035 $cm^{-2}\,s^{-1}$ is feasible. But there's still a lot of work to do, both in accelerator physics and key technologies. Experienced accelerator physicists and engineers are needed all around the world, therefore, besides world-wide recruitment, work together with international colleagues should definitely be an option for either project.

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