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The project of the Super Charm-Tau Factory in Novosibirsk

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Abstract. Electron-Positron collider Super Charm-Tau factory at the Budker Institute of Nuclear Physics (BINP) will operate at energies in center of mass W=2 – 6 GeV with unprecedented high luminosity of $10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and the longitudinal polarization of the electrons at the interaction area. The main purpose of the experiments at the collider is search for effects of CP-violation in the decays of charmed particles, tests of the Standard Model in the decay of the τ-lepton, the search and study of an entirely new forms of matter: glueballs, hybrids, etc. The data, which are planned to record, by 3 – 4 orders exceed everything that has been recorded so far in any other experiment in this energy range. Conceptual designs of the collider based on crab-waist technique and universal detector are developed and presented. Preliminary physics program are considered. Progress of R&D for detector systems are given.

1. Introduction

The Super Charm-Tau (SCT) factory is an electron-positron collider project in Novosibirsk with a peak luminosity of 10^{35} $\mathrm{cm}^{-1}\mathrm{s}^{-1}$ operating in the center of mass energy range between 2 and 6 GeV [1]. The goal luminosity of the collider will exceed in 100 times the luminosity of the BEPC-II (Beijing Electron-Positron Collider, China) [2], which is under operation today in the same energy range. The other feature of the project is a high level (80 – 90%) of longitudinal polarization for the electron beam at the interaction point. The proposed collider machine with high luminosity and beam longitudinal polarization combined with high performance universal detector will allow us to provide a series of precise experiments and tests of the Standard Model (SM).

According to the European strategy for Particle Physics Update 2020 [3] precise experiments to search for new physics beyond the SM are very demanded in the near future. The physics experiments with SCT factory will fit this strategy very well.

2. Some consideration of the preliminary physics program

In Figure 1 the ratio (R) of hadron production cross-section to muon production cross-section is shown for the energy range of the Novosibirsk SCT factory. The operation energy range from 2 GeV to 6 GeV will cover the thresholds of τ - lepton production and almost all charmed states up to region of the Ω_c-baryon. The physics program of the experiment is devoted to the measurements of charm quark and tau lepton. It includes precision tests of the SM in the electro-weak sector (lepton flavor universality tests, measurement of the CKM matrix elements,

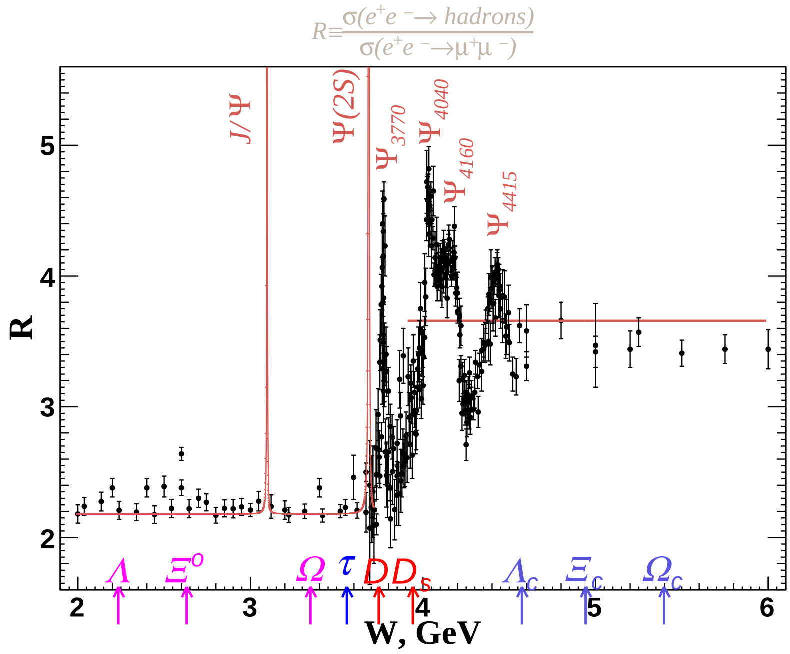

Figure 1. R ratio for SCT factory operation energy range.

measurements of the weak charged current structure in tau decays), QCD measurements in the non-perturbative region (hadronic cross sections, spectroscopy, dynamics of the hadronic decays of the charmed hadrons and τ-lepton), and searches for the beyond SM phenomena (lepton flavour violating decays and other forbidden or highly suppressed in the SM processes).

During 10 years of operation of the SCT factory the integrated luminosity will be about 10 ab^{-1}. The total statistics of the τ-leptons, D, D* and D$_s$-mesons will not exceed the statistics expected at the Super-B factory (Belle II experiment) and already collected at the LHCb experiment. Nevertheless the project has several advantages which will help to perform a series of precise experiments:

- threshold production;
- well determined initial state;
- quantum correlated production of D^0 meson pairs;
- double tag technique;
- low multiplicity (4-5);
- longitudinal beam polarization.

Some feasibility studies demonstrate that sensitivity of the SCT factory project to τ-lepton physics will be better than at the Super-B factory and at proton colliders. For instance, sensitivity to search for $\tau \to \mu\gamma$ process (LFV in τ-decay) at the SCT factory will be 10 times better than at the Super-B due to better kinematics of the τ near the threshold of production and due to good μ/π-separation in dedicated particle identification (PID) system [4, 5]. The longitudinal polarization of the electron beam better than 50% will help to perform more accurate measurements of the τ-lepton Michel parameters than expected at the Super-B factory [6]. The other feasibility studies for other physics cases now are under consideration.

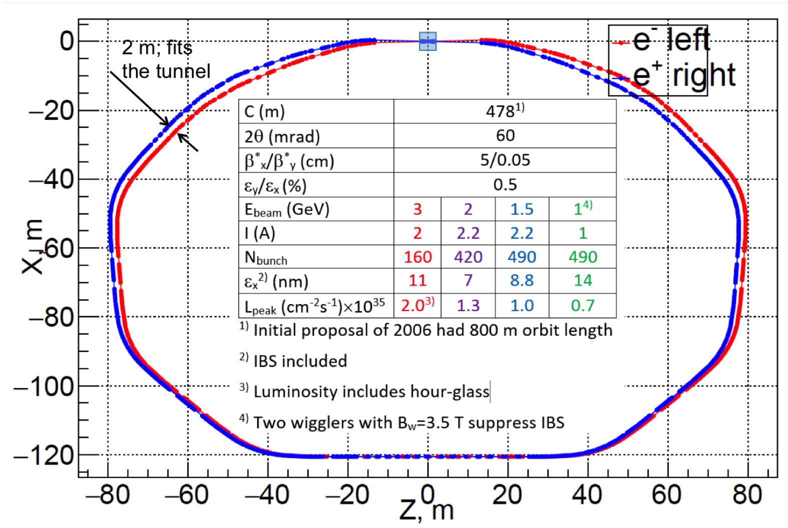

Figure 2. The scheme and main parameters of the collider rings for the Super Charm-Tau factory project.

3. Collider concept

The SCT factory is a symmetric double ring electron-positron collider. The high single-bunch luminosity is achieved by implementation of Crab–Waist collision scheme with a large Pivinsky parameter and submillimeter β_y (vertical beta-function) in interaction region. Today only two collider projects with the large Pivinsky parameter are under operation: the DAΦNE (LNF, Italy) [7] and the SuperKEKb (KEK, Japan) [8]. In the first case this collision scheme helps to increase the luminosity approximately by 4 times, in the case of SuperKEKb project an increase of luminosity by 40 times is expected. The estimated effect from implementation of the new collision scheme for the SCT factory is about a factor of 100 in comparison with the traditional one which is used at the Chinese C-τ factory BEPC-II (IHEP) [2].

The first collider concept was developed in 2011 and its main parameters are presented in [10]. In 2019 the concept of accelerating complex was updated. The main parameters of modern accelerator concept:

- circumference is 478 m;
- beam crossing angle (2Θ) is 60 mrad;
- beam energy range is from 1 to 3 GeV/c;
- number of bunches is up to 490
- current is from 1 to 2.2 A;
- beta-function in interaction region (β_x/β_y) is 5/0.05 cm;
- peak luminosity is expected from 0.7 to $2.0{\cdot}10^{35}\text{cm}^{-1}\text{s}^{-1}$ for different energy ranges.

The sketch of the collider rings and main parameters of the renewed concept are presented in Figure 2. The renewed accelerator complex concept has no unsolved issues, prototyping of key components of the accelerator complex is being carried out at the BINP.

3.1. Beam polarization.

The one of the major features of the SCT factory project in Novosibirsk is a longitudinal electron beam polarization in interaction region. The accelerator concept was optimized for scheme with

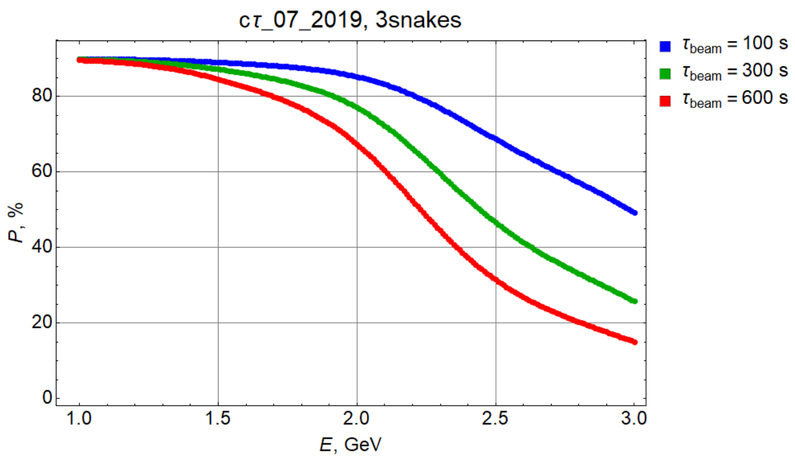

Figure 3. Dependence of beam polarization level on beam energy for three different periods of injection repetition: 100 s (blue), 300 s (green), 600 s (red).

three Sibirian Snake spin rotators [9]. In this scheme 70-80% electron beam polarization for beam energy range below 2.5 GeV is expected and 50% polarization at 3 GeV is foreseen. In Figure 3 the dependences of the beam polarization level on beam energy are shown for three different periods of injection repetition: 100 s (blue), 300 s (green), 600 s (red).

4. Detector

The proposed broad physics program requires construction of a universal high performance magnetic detector with a field of 1 − 1.5 T. The scheme of the proposed detector is shown in Figure 4. The common requirements for the detector from physics program and collider parameters are following:

- good momentum resolution $\frac{\sigma_P}{P} \leqslant 0.4\%$ at 1 GeV/c for charged particles;
- good symmetry and hermeticity;
- soft track with momenta from 50 MeV/c detection;
- μ/π-separation up to 1.5 GeV/c and π/K-separation up to 2.5 GeV/c at the level of better than 3 standard deviations (σ);
- good π^0/γ-separation and γ detection with E_γ=10÷3000 MeV;
- energy measurements resolution $\frac{\sigma_E}{E} \leqslant 1.8\%$ at 1 GeV;
- fast enough readout electronics to work with trigger rate up to 300 kHz.

The other requirements on detector systems and their capabilities come from background conditions. The first results of physics background simulation were obtained and presented in [12]. There were considered only two physics processes: BhaBha scattering ($e^+e^- \rightarrow e^+e^-\gamma(n\gamma)$, total cross-section with Θ >5 mrad and E_γ >3 MeV is ∼1.7 mb) and two gamma production of e^+e^- pairs ($e^+e^- \rightarrow \gamma^*\gamma^* \rightarrow e^+e^-e^+e^-$, total cross-section for electron and positron beams with E=3 GeV is ∼6 mb). The main results of simulation:

- neutron dose is $\leqslant 10^{11} n_{eq} cm^{-2}$/year;
- for peak luminosity $10^{35}\mathrm{cm}^{-1}\mathrm{s}^{-1}$ and bunch crossing rate $2 \cdot 10^8\mathrm{s}^{-1}$ up to 4 charged background particles could appear in sensitive detector volume per each event;
- due to detector magnetic field and material budget the flux $10^4 \div 10^5 \frac{\mathrm{electron}}{\mathrm{cm}^2 \cdot \mathrm{s}}$ in the region of the inner tracker (30⩽radius⩽200 mm) is expected;

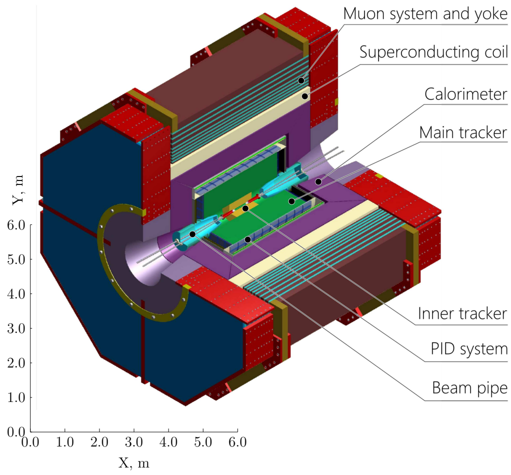

Figure 4. The detector conceptual scheme for the SCT factory in Novosibirsk.

4.1. Tracking system.

The tracking system is divided in two parts: inner tracker to detect soft tracks (with momentum below 100 MeV/c) and main tracker based on drift chamber (DC).

4.1.1. Inner Tracker. For the inner tracker several different options are under consideration: a Si-strip 4-layer detector, a cylindrical GEM (Gas Electron Multiplayer) and a TPC (Time-Projection-Chamber) [11]. The main limitation for use of different options close to the interaction region comes from the physics background [12]. According to the first results of simulation the TPC option allows to detect pions with transverse momentum from 50 MeV/c (pions with lower momentum are not able to cross the vacuum central pipe). The other options (CGEM and Si-Strip) are able to detect pions with momentum higher than 80 MeV/c. Also the TPC option could provide more reliable dE/dx measurements for particles identification with low momenta.

4.1.2. Drift Chamber. For DC there are two proposals. One of them is called “traditional” which is based on hexagonal drift cell with size 6÷7.5 mm, 41 layers combined into 10 super-layers with alternating axial and stereo layers [13]. The gas mixture He/C_3H_8 (60/40) is considered. The expected main parameters are following:

- $\sigma_x \leqslant 90\mu$m;
- $\frac{\sigma_P}{P}$(1 GeV/c) $\sim 0.38\%$;
- $\frac{dE}{dx}$-resolution ~7%.

The second proposal is called “ultra low mass DC” with rectangular cell 7.2×9.3 mm^2, 64 stereo layers, total number of very thin wires is about 100000 [14] and gas mixture He/iC_4H_{10} (90/10). The major idea of this approach is to decrease as much as possible the impact to momentum resolution from Coulomb multiple scattering of particles in materials of DC. In both cases R&D for new readout electronics is needed. If the readout electronics will provide the cluster counting it could help to improve the $\frac{dE}{dx}$-resolution approximately by two times and extend the momentum range for reliable particle identification with help of the tracking system.

4.2. Particle identification system.

A dedicated PID (Particle IDentification) system is needed to provide π/K and μ/π-separation with more than 3σ level in momentum ranges $0.6 - 2.5$ GeV/c and $0.2 - 1.2$ GeV/c, respectively. The lowest momentum (0.2 GeV/c) is determined by magnetic field of detector in which charged particles will not reach the dedicated PID system (radius $\geqslant$800 mm). The Focusing Aerogel RICH (FARICH) technique is able to provide required π/K-separation and excellent μ/π-separation in momentum range from 0.45 GeV/c up to 1.5 GeV/c. It was demonstrated with simulation and the prototype beam test at CERN in 2012 [15, 16]. Recent results on FARICH R&D are presented in [17]. The aerogel with refractive index n=1.05 has the threshold of Cherenkov radiation for muons at 0.33 GeV/c and for pions at 0.45 GeV/c, therefore we need to look for alternative PID options such like DIRC, ToF (Time-of-Flight) and ToP (Time-of-Propagation) which able to provide good μ/π-separation from 0.2 up to 0.45 GeV/c. To provide good μ/π-separation in required momentum range it is possible to develop FARICH system based on multi-layer focusing aerogel with maximal refractive index n=1.07, but today it is still very challenge issue. The other possibility to use some combination of PID approaches ToF or DIRC-like-ToF technique with 30 ps time resolution and aerogel Cherenkov threshold counters ASHIPH (Aerogel, Shifter, PHotomultiplayer) [18, 19]. In this case it is very important to estimate impact of additional material budget on electromagnetic calorimeter energy resolution.

4.3. Calorimeter.

The main tasks of the electromagnetic calorimeter are to provide good π^0/γ-separation and γ detection with E_γ=10÷3000 MeV. Energy resolution better than 1.8% at 1 GeV is expected according to the conceptual design report. Also the calorimeter should be fast ($\sigma_t \leqslant$1 ns and small shaping time) to suppress beam background and pileup noise. Therefore as a base option the calorimeter based on pure CsI crystals with decay time about 36 ns is considered. The recent R&D at BINP shows that light output from the pure CsI-crystals could be increased almost by 6 times by using 4 avalanche photodiodes (APD) and wavelength shifter (WLS) with specific shapes [20]. The prototype of calorimeter for SCT factory project based on matrix of 16 crystals is shown in Figure 5 (right). The WLS plate caoted with novel nanostructured organosilicon luminophores (NOL-9) is presented in Figure 5 (left). The specific shapes of the WLS plate was obtained during the optimization of the light collection efficiency from the crystal on 4 APDs connected to the plate through a chamfer in each corner.

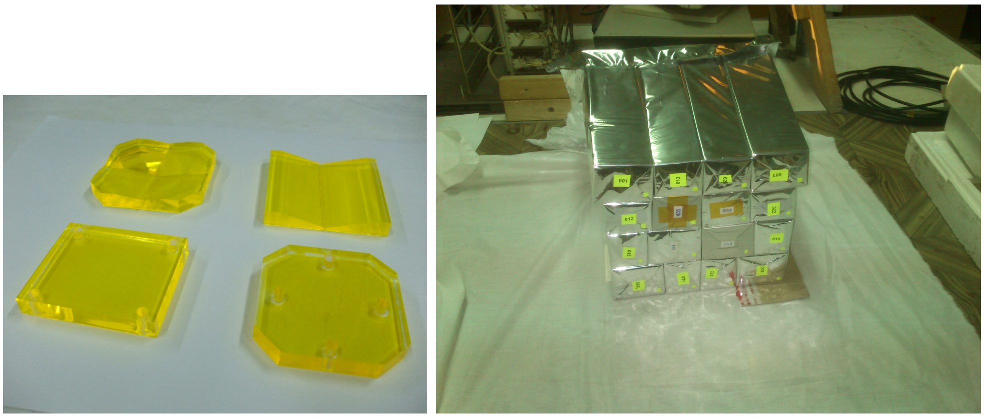

Figure 5. Prototype of calorimeter based on pure CsI crystals and WLS: WLS based on plexiglass coated with NOL-9 (left) and matrix of 16 crystals prepared for beam tests (right).

4.4. Muon system.

To separate muons from hadrons the muon system placed in the 9 gaps of the yoke iron will be used. The option of the muon system for the SCT factory project based on a scintillating plastic and WLS fibres coupled to SiPMs (Silicon Photomultiplayer) is being developed in LPI (Moscow). Some details and R&D progress are presented in [21]. The system with proposed construction also could be used to detect K_L-mesons.

5. Summary

The Super Charm-Tau factory is one of the five megascience-class projects approved for implementation by the Russian government. The construction of the new electron-positron collider is a flagship project for the Budker Institute of Nuclear Physics (BINP). The physics program of the project will compliment the other current and future High Energy Physics experiments such as Belle II, LHCb and FCC [3]. Expected parameters of the collider and detector allow us to increase significantly the sensitivity of the experiment for new physics searches beyond the Standard Model. The process of forming an international collaboration to perform a broad physics program, develop final designs of the collider and the detector, and subsequently commence construction is underway. R&D with prototyping for several systems of the collider and detector have been started in BINP and in several foreign institutes.

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