Precision experiments at electron-positron collider Super Charm-Tau Factory

A contribution to the Update of the European Strategy for Particle Physics

Budker INP, Novosibirsk

Contact persons:

Eugenie Levichev (E.B.Levichev@inp.nsk.su), Alexander Bondar (A.E.Bondar@inp.nsk.su), Yury Tikhonov (Iouri.Tikhonov@cern.ch), Ivan Logashenko (I.B.Logashenko@inp.nsk.su)

Abstract

This document describes research program of Budker INP (Novosibirsk) on high energy physics for the next two decades based on the flagship project of the electron-positron collider Super Charm-Tau (SCT) factory. The SCT factory is designed to operate in the center-of-mass energy range from 2 to 6 GeV with peak luminosity of $10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ above 4 GeV. Longitudinal polarization of the electron beam at the interaction region enhances the collider discovery potential. The facility, equipped with a state-of-the-art universal particle detector, allows precision measurements of decays of tau lepton and hadrons formed by quarks of the two first generations.

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Introduction

Experiments at the Large Hadron Collider (LHC) constituted the focus of the high energy physics community during the last decade. After the discovery of the Higgs boson, strong efforts (not yet successful) were applied to searches for new physics, mainly, supersymmetric partners of the fundamental particles. Meanwhile, interesting phenomena have been observed in the Belle, BaBar, BESIII, and LHC*b* experiments: many new resonances being interpreted as multiquark states (X, Y, Z families, Z_b and P_c mesons). There is no consensus about the origin of the new states, because we do not yet have a theory to describe strong interactions at this energy.

The LHC*b* experiment continues the program of precision measurements of heavy flavors and continuously provides many interesting results. Evidence for the flavor universality violation in $b \to c$ and $b \to s$ transitions constitutes the strongest hint to presence of the New Physics from current particle collider experiments. In this context, continuation of the program of precision measurements is of great importance for development of new theoretical approaches within the standard model and *indirect* searches for new physics.

There are three complementary experimental approaches to charm physics in collider experiments: a) threshold production (experiments CLEO-*c* and BESIII), b) *B*-factories (experiments Belle and BaBar) and c) precision studies in proton collisions (experiment LHC*b*). Each approach has advantages and disadvantages and it is important to have synergy of the three. Threshold experiments have unique access to coherent pairs of neutral *D* mesons and best capability to measure charm decays with neutral and non-interacting final-state particles. In the next ten years the current balance of three approaches is going to be lost: *B*-factory experiments are going to be boosted with the Belle II measurements; the LHC*b* detector has rich upgrade plan and is going to increase the recorded statistics by one or two orders of magnitude. In contrast, threshold charm experiments do not have comparable progress yet. Without threshold data, the physics potential of the Belle II and LHCb cannot be fully revealed. The SCT factory proposed in Budker INP is designed to restore this abovementioned synergy.

A SCT factory experiment is also an influential actor in the tau lepton physics. Despite the large tau data set collected by the *B*-factories, many world-best results are still based on analysis of the LEP collider experiments (hadronic spectral functions etc.). Many *B*-factory measurements on tau lepton (lepton universality test etc.) are limited by systematic uncertainties; tau physics is not in the focus of *B*-factory community, so that many analyses have been never done. A high luminosity machine with a particle detector designed for precision tau physics, such as the SCT factory, is able to change the current situation and help develop this not-yet-explored and underestimated field of particle physics. A data set of tau leptons produced near the threshold gives advantages for several key measurements (hadronic spectral functions, search for lepton flavor violating decays etc.). Longitudinal polarization of the electron beam, foreseen in the SCT factory project, increases sensitivity in searches for possible *CP* symmetry violation in tau decays and helps a lot in measurements of the Lorentz structure of tau decays.

Physics case

The energy range ($\sqrt{s}$ from 2 to 6 GeV) of the SCT factory will allow us to produce all leptons and light hadrons, and most of charmed hadrons. Yields of tau leptons and charmed hadrons to be obtained at the SCT factory with luminosity of $10^{35}\ \mathrm{cm^{-2}s^{-1}}$ during a year are listed in Table 1.

Table 1. Approximate annual yields of the SCT factory

Particle type	J/ψ	$\psi(2S)$	$D\bar{D}$	$D_s^+D_s^-$	$\tau^+\tau^-$	$\Lambda_c^+\Lambda_c^-$
Number of states produced annually	10^{12}	10^{11}	10^{9}	10^{8}	10^{10}	10^{8}

The SCT data set would allow us to do precise tests of electroweak theory in charm and lepton sectors and measurements of hadron spectroscopy important for intermediate-energy non-perturbative QCD. Physics program of an experiment at the SCT factory is rich and extensive; it can be divided into the following chapters: a) charmonium, b) charmed mesons, c) charmed baryons, d) tau lepton physics, e) two-photon physics, i) initial-state radiation (ISR). Highlight examples of physics tasks for the SCT factory are briefly mentioned below.

Charmonium

The knowledge of charmonium family is far from complete. Only about 45% of hadronic decays of the J/ψ meson, the best-studied charmonium state, have been measured. A large and clean data set to be collected at the SCT factory allows to perform a systematic study of the charmonium family, including observation of weak decays of the J/ψ meson governed by the $c \to s$ transition.

A large number of charmonium(-like) states above the open charm threshold of unclear nature ($X(3872), \ldots, Y(4260), \ldots$, $Z(3900), \ldots$) has been discovered over the last 15 years. Systematic and precise measurements of these states are required to understand their nature and can be performed at the SCT factory.

Decays of J/ψ mesons are a unique source of light states composed from light u, d, and s quarks. Their spectroscopy is another complicated field where many studies are needed to be done. There could be light resonances that are mixtures of conventional meson and glueball or light tetraquark states. It is a challenging task to identify these states. The SCT data set is best suited for this purpose.

Charmed mesons and baryons

Several world-best measurements of charmed hadrons can be performed with the SCT factory data set, even though both LHC*b* and Belle II experiments will gain larger yields of charmed mesons. Threshold production of charmed hadrons provides clean background environment, well-known initial state, low multiplicity of final-state-particles and additional kinematic constraints. These advantages make a SCT factory data set nearly perfect to study decays with neutrals, neutrinos, K_L^0 mesons and any “invisible” final-state particles. The double-tag technique provides a straightforward way to measure absolute branching fractions of charmed hadrons.

Coherent production of neutral *D* meson pairs at threshold makes *D* meson decay rates sensitive to the phases of decay amplitudes via quantum correlations. Dedicated approaches utilizing quantum correlations allow us to measure charm mixing and CP symmetry violation in charm without measuring *D* meson proper decay time.

Tau lepton

Many measurements of tau lepton properties at *B*-factories are limited by systematic uncertainty. A large data set of tau leptons produced at threshold allows one to reach new precision frontiers of tau physics in several directions: universality of *W* boson coupling to leptons (lepton universality); search for CP violation via triple product asymmetries (reinforced by full kinematic reconstruction); tau lepton mass determination; Lorentz structure of leptonic tau lepton decays by measurements of Michel parameters; two-body (semi-)hadronic decays of tau leptons (with monochromatic final-state hadrons); measuring the strong coupling $\alpha_s(m_\tau)$ and CKM element V_{us} in inclusive tau decays with the odd number of kaons; measuring the low-energy QCD parameters in tau hadronic decays; search for lepton flavor violating decays, for example, $\tau \to \mu\gamma$.

Two-photon physics

In contrast to single-photon e^+e^- annihilation, where the quantum numbers of the final state are fixed to $J^{PC} = 1^{--}$, in two-photon production the hadronic final state always has positive C-parity, while various J^P are possible. This feature makes possible a measurement of basic properties, such as mass, total and two-photon width, of several hadronic resonances and confront the results with predictions of various theoretical models. Huge integrated luminosities expected at the SCT factory allow high-precision determination of resonance parameters for well-established states and confirmation or even discovery of rare or high-mass states including charmonia with mass up to about 4 GeV.

A study of W dependence of the cross section, where W is invariant mass of the produced hadronic system, allows a test of predictions of asymptotic QCD to be performed as it has been shown by Belle for various two-body final states. At the SCT factory such measurements can be continued to increase precision and make clear conclusions about validity and range of QCD applicability. One can also try to extend this method to other more complicated states, e.g. those with three final hadrons.

It is very interesting to measure the Q^2 dependence of single- and double-tag mode production (one and both detected electron or positron plus a hadronic system) for various pseudoscalar final states, like $\pi^0\eta$ and $\pi^0\pi^0$, and determine from it transition form factors, important not only for QCD tests but also for dispersive estimation of the hadronic light-by-light contribution to the muon anomalous magnetic moment. Here Q^2 is the squared mass of the virtual photon and from experience of BaBar, Belle and BESIII it is clear that measurements at the SCT factory will allow to reach a region of very low Q^2, important for the muon anomaly.

Initial-state radiation

A detailed study of the hadron production in e^+e^- annihilation at low energies provides valuable information about interactions of light quarks and spectroscopy of their bound states, which is invaluable input to construction of theoretical models describing the non-perturbative regime in QCD.

Precise measurements of exclusive cross sections of e^+e^- to hadrons are especially important for theoretical calculations of the muon anomalous magnetic moment in Standard Model in view of the present difference between theoretical and experimental values exceeding three standard deviations. In 2017 a new muon $(g-2)$ experiment, FNAL E989 started data taking. This experiment is based on the same principles as the previous one and reuses the same muon storage ring. Another project, E34, based on a completely different approach is under development now at J-PARC in Japan. The data on e^+e^- cross sections available now are obtained in two types of experiments: in the scan of the energy and at the constant energy of the experiment and detection of the processes with a hard photon emitted from the initial state (ISR). An accuracy of both types of data is stated to be about 1%. However, the target precision of both $(g-2)$ experiments requires an improvement of the hadronic cross section precision by at least two times. This challenging task can be solved by a careful cross check using various approaches and detectors including an ISR approach.

Complementarity to Belle II and LHCb experiments

There are two main places where the Belle II and LHC*b* experiments need input from near-threshold measurements at the SCT factory.

Beauty hadrons are of primary interest in the Belle II and LHC*b* experiments. Most of their decays proceed through charmed hadrons (via $b \to cX$ transition). That is why some measurements of beauty hadrons depend on branching fractions of charmed hadron decays. As already mentioned, double tag technique at threshold provides a straightforward way for precise measurements of absolute branching fractions of charmed hadron decays in the SCT experiment.

The measurement of Cabibbo-Kobayashi-Maskawa (CKM) phases is a central part of physics program of the Belle II and LHC*b* experiments. The CKM phase γ is measured in $B^{\pm} \to DK^{\pm}$ decays and depends on a phase of D meson decays to hadronic final states like $K\pi$, $K\pi\pi^0$ and $K_S^0\pi^+\pi^-$. The CKM parameter $\cos 2\beta$ can be measured in the decay $B^0 \to D\pi^0$ with $D \to K_S^0\pi^+\pi^-$. This measurement requires information about the phase of the $D \to K_S^0\pi^+\pi^-$ decay amplitude. Similarly, charm phases are required to measure charm mixing parameters. A model-independent approach to the mentioned tasks requires a measurement of charm phases in threshold experiment using quantum correlations. Estimates show that LHC*b* statistics after the phase II upgrade would require threshold results with precision not reachable today in the BESIII experiment.

Measurements with polarized electron beam

The SCT factory is going to be the first new generation flavor factory with a longitudinally polarized electron beam. The discovery potential of this feature is yet to be fully revealed, nevertheless, current understanding gives enough motivation to implement longitudinal polarization.

The electron polarization gives a clear advantage in studies of the Lorentz structure of tau lepton decay. The Lorentz structure is determined by four Michel parameters, and a measurement of two of them requires non-zero tau lepton polarization. This limitation can be bypassed with exploitation of spin-spin correlation of nonpolarized tau lepton pairs leading to a complicated analysis in the 6D phase space. Well-controlled initial polarization of tau lepton gives an opportunity to measure all four parameters in decays of single tau leptons. The Michel parameters of tau decays can be measured with world-best precision at the SCT factory with a polarized electron beam.

Polarization allows to determine the Weinberg angle from difference of total cross sections with opposite electron' helicities and to measure CP violation in angular distributions of tau lepton and charmed baryon decays.

Accelerator complex

In the flat beam collisions small vertical beta function β_y^* at the interaction point (IP) is necessary to achieve high luminosity. However, due to the divergence of the beam β_y^* is limited by the bunch length σ_z (hour-glass effect). Decrease of bunch length is not possible due to the growing influence of the collective effects. For representative beam current of 1-2 A the achieved bunch length is 6-10 mm, which limits the minimal vertical beta function and luminosity of the traditional electron-positron colliders. Proposed in 2006 Crab Waist (CW) collision scheme increases luminosity of e^+e^- colliders up to two orders of magnitude without reduction of the bunch length or increase of its intensity. In the new collision scheme beams collide with the crossing angle 2θ in the horizontal plane (Figure 1), providing large Piwinski angle. The length of the interaction area (overlap of the beams) becomes significantly smaller than the bunch length allowing reduction of the vertical beta function β_y^* without enhancement of the hour-glass effect. The crossing angle collision also solves the problem of parasitic beam crossing; the beams separation is equal to several horizontal beam sizes at the distance of the bunch length. This naturally leads the electron and positron beams into the separate rings, giving a possibility to work in the multibunch regime.

Beam collision with a large Piwinski angle intensifies the synchro-betatron coupling resonances. Installation of the two sextupoles on both sides from the IP, at certain betatron phase advances and with proper strength, eliminates the synchro-betatron coupling resonances. The Crab Waist collision scheme was experimentally tested at the Φ-factory DAΦNE (Frascati, Italy).

The chosen collision scheme and lattice provide luminosity $(0.7 \div 2) \times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ at beam energies from 1 to 3 GeV. Table 2 presents the main parameters of the SCT factory. In order to decrease damping times at 1 GeV it is necessary to install one damping wiggler with 3.5 T field and 1.5 m length.

Table 2. Main parameters of the SCT factory

Beam energy E [MeV]	1000* (+wiggler)	1000	2000	3000
Circumference Π [m]	522			
Crossing angle θ [mrad]	± 30			
β_x^*/β_y^* [mm]	50 / 0.5			
Beam current I [A]	2.2	2.3	2.2	2.2
Bunch population $[10^{10}]$	5.5	7	6.7	9
Number of bunches	440	360	360	270
Horiz. emittance $\varepsilon_x(rad)/\varepsilon_x(IBS)$ [nm]	0.5/10	0.5/15	2.1/4.3	4.8/5
Emittance ratio $\varepsilon_y/\varepsilon_x$	0.005			
Energy spread $\sigma_e(rad)/\sigma_e(IBS)$ $[10^{-3}]$	0.3/2	0.3/1.8	0.6/0.93	0.93/0.96
Bunch length $\sigma_z/\sigma_z(IBS)$ [mm]	3.2/13	3.2/11	6.7/10	8.8/9.1
RF voltage V_{RF} [kV]	11	11	176	894
Momentum compaction	5.5×10^{-4}			
Damping times $\tau_x/\tau_y/\tau_z$ [ms]	100/100/50	300/300/150	40/40/20	12/12/6
Beam-beam tune shift ξ_x/ξ_y	0.006/0.12	0.004/0.1	0.004/0.12	0.005/0.11
Hour glass [%]	78	73	86	85
Luminosity $[10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}]$	0.9	0.7	2	2.8

Figure 1 shows general configuration of the SCT factory. Five Siberian Snakes provide polarization level of 80-90% at the beam energy range from 1 to 3 GeV.

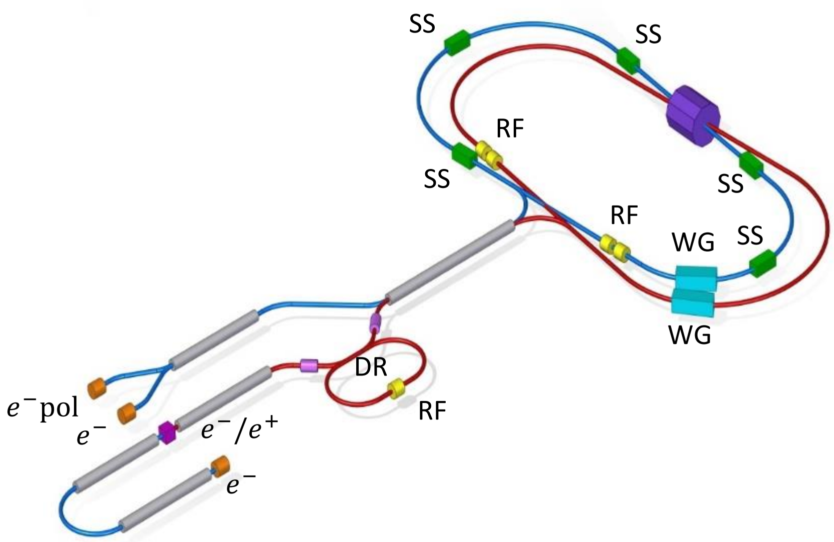

Figure 1. General configuration of the SCT factory. WG- damping wiggler, SS – Siberian snake, RF – accelerating cavity, DR – damping ring (1-1.5 GeV), e^-pol – polarized electron source, e^- – electron source, e^-/e^+ – conversion system.

Detector

Reaching the physics goals of the SCT experiment requires a universal magnetic detector. The detector should meet several requirements: excellent momentum resolution for charged particles and good energy resolution for photons; outstanding performance of particle identification system in comparison with the existing detectors; digitizing electronics and a data acquisition system capable to readout events with 300 kHz rate and 30 kB event size; trigger capable to select events and to reject background at that high detector occupancy.

The detector includes a standard set of subsystems (Figure 2): inner tracker, main tracker, particle identification system, electromagnetic calorimeter, superconducting solenoid, iron yoke with a built-in muon system. Front-end electronics inside the detector performance a digital conversion of signals and transmits digital information via 10 Gbps optical links.

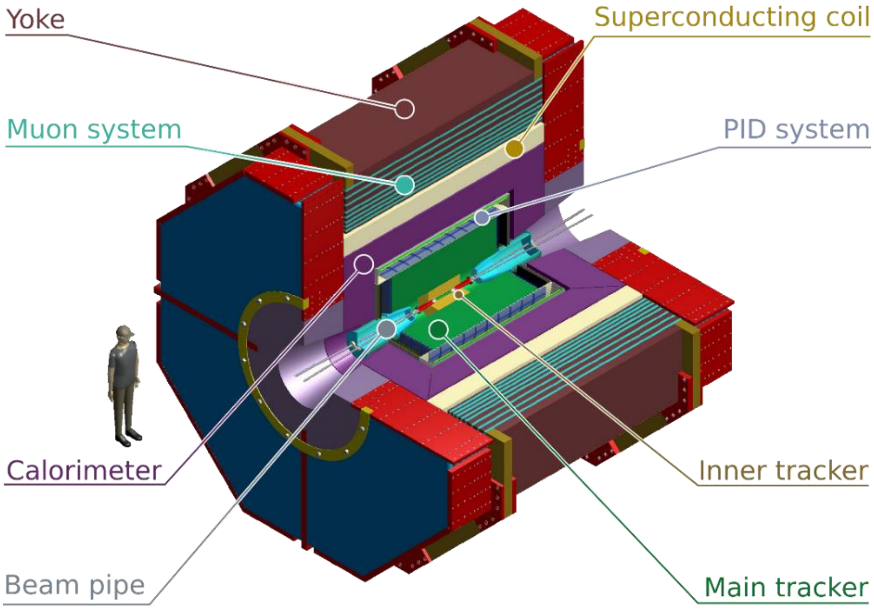

Figure 2. Detector for the SCT factory: 1 - inner tracker; 2 - main tracker; 3 - PID system; 4 – EM calorimeter; 5 - superconducting solenoid; 6 - magnet yoke and muon system.

Besides, there are outer detector systems and services including trigger and data acquisition system, data centers, magnet cryogenic system, engineering complex. Table 3 and Table 4 briefly describe the purpose and the status of the detector components.

Table 3. Detector subsystems

Subsystem	**Purpose**	**Options**	**Status**
Inner tracker	Precise measurement of the position of the tracks originating point (vertex)	Time projection chamber (TPC) with micropattern gaseous detectors, 4-layer cylindrical GEM detector, stack of silicon strip layers, compact straw tubes	TPC technique is new for the accelerator experiments. A few prototypes exist. Possible alternative – traditional silicon microstrip detector. Application-specific integrated circuit chips (ASIC) are required for the front-end electronics.
Main tracker	Measurement of trajectories and momenta of charged particles in magnetic field, particle identification, charged trigger	Drift chamber with traditional hexagonal cells, low mass drift chamber with cluster counting	This well-established technique has been world-wide employed for decades, including Budker INP.

Particle identification system	Identification of charged particles that cannot be performed by other subsystems	Focusing Aerogel-based Ring Imaging Cherenkov detector (FARICH), threshold Cherenkov aerogel counters (like ASHIPH)	This unique technique employs multilayer aerogel for focusing Cherenkov light that improves PID performance. A small scale FARICH prototype has been built and tested; the obtained parameters are as expected. Detector magnetic field requires the usage of silicon photomultipliers (SiPM), rather expensive now. ASICs are required for the front-end electronics.
Electromagnetic calorimeter	Measurement of the photon energy, identification of electrons and positrons, neutral trigger	Crystals of inactivated (pure) CsI	Budker INP has large experience of using alkali halide crystals NaI and CsI in the calorimetry: ND, SND, CMD-2/3, KEDR detectors. Budker INP developed and produced calorimeter counters for the Belle II and WASA experiments. A similar calorimeter using inactivated CsI is being developed for the SuperKEK*B* factory project.
Superconducting solenoid	Provides a magnetic field inside the detector for the charged particle momentum measurement	Traditional - all detector subsystems are in the magnetic field and superconducting coil placed behind the calorimeter, thin superconducting coil with thickness about 10% of radiation length placed behind the main tracker	Budker INP has large experience of making and running big superconducting solenoids for detectors: CMD-2, KEDR, CMD-3
Muon system	Muon identification	The coordinate detectors are alternated with layers of a steel absorber, which also serves as the yoke of the magnet	The choice of the detection technology of coordinate chambers requires a study of their long-term stability and resistance to the backgrounds under the experimental conditions of SCT

Table 4. Outer systems and services of the detector

System	Description	Status
Trigger and data acquisition system (TDAQ)	DAQ provides the on-line acquisition of digitized signals from the detector, calculation of signal timings and amplitudes, event building and transmission of information to the data centers. During DAQ the information passes the hardware (low level) and software (high level) triggers that select only useful events using hits in a number of subsystems.	Conceptual design has been based on the Budker INP experience and that of international HEP experiments: BaBar, Belle, ATLAS, CMS, etc. Existing solutions for read-out, transmission and processing of information are used.
Data Centers	Computing farms for on-line and off-line data processing with combined performance of 0.5 petaflops, HDD and tape-based storage systems with total capacity of 240 petabytes and fiber-optic communication lines with internal connectivity of 1000 Gbps.	Conceptual design has been made using world HEP experiment experience. A model of the off-line data processing, storage and distributed analysis is being developed. Possibilities of using external computing resources (GRID-systems, Cloud-platforms) are being considered. Analysis of cost and feasibility of creating a computing infrastructure for SCT factory is based on the published computer industry researches.
Engineering complex	Supplies power, heat removal from the detector and equipment, ventilation, gas mixtures for the subsystems, enables a relocation of the detector and removable parts of radiation protection. Special attention is paid to ensuring safety of the personnel, prevention of accidents and fail-safe operation of the detector.	Conceptual design has been made. Simulation of radiation protection has been performed. It is considered to use external contractors for building a number of systems.

Project readiness and expected challenges

The SCT factory project is in state of R&D and realization planning. Two billion Rubles (approx. 27 MEuro) have been invested in the detector and accelerator R&D, planning and civil construction of the SCT factory including injection complex, buildings and tunnels. Civil construction project draft for the SCT infrastructure has been prepared (Figure 3).

The SCT project became one of the six mega-science projects selected by the Russian Governmental Commission for implementation in 2011. The SCT physics, detector and accelerator Conceptual Design Reports has been made (https://ctd.inp.nsk.su/c-tau/) and are being permanently refined. The SCT project roadmap (appendices to roadmap) contains preliminary timeline and budget has been written.

The SCT project was included in the plan for the implementation of the first phase of the Strategy for Scientific and Technological Development of the Russian Federation in June 2017.

Russian Ministry of Education and Science and Budker INP signed an agreement for 250 million Rubles in August 2017, which foresees the development and upgrade of the accelerator complex of Budker INP and the creation of scientific and technical groundwork for the implementation of the SCT project.

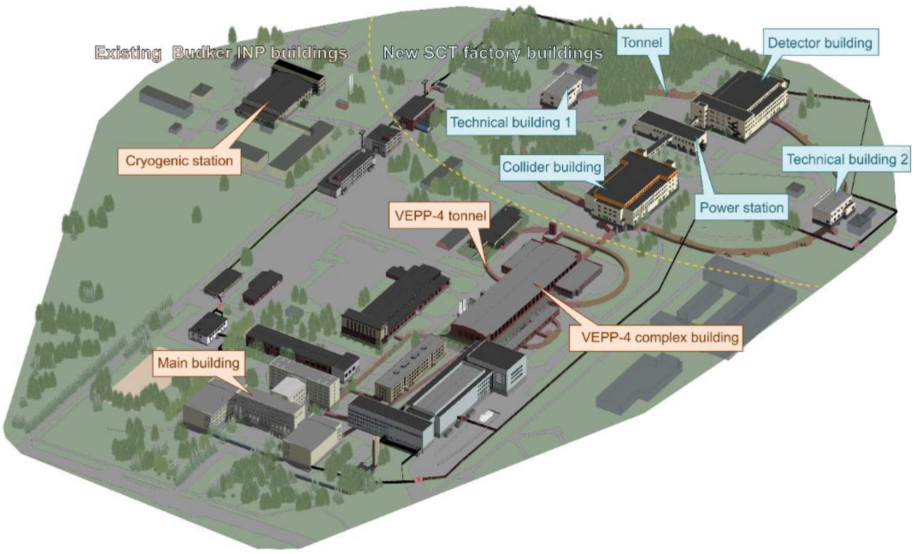

Figure 3. Existing and new buildings and underground tunnels for the SCT accelerator complex.

International Advisory Committee (IAC) of the SCT detector composed by 13 acknowledged scientists is formed (the list of names is in the addendum A). The first IAC meeting was held in May 2018 in Budker INP. The IAC stressed out a good expertise of Budker INP community in particle accelerator and detectors technologies, expressed strong support of the SCT project, and issued a list of recommendations. These recommendations compose the basis of the current activity.

An important part of current activity is physics simulation of the SCT experiment. Wide simulation efforts are required to establish detailed physics program and to elaborate requirements for the detector subsystems and parameters of colliding beams in the interaction region. With this purpose a software framework is developed. The framework is based on well-known in HEP community software: Gaudy, ROOT and Geant4. It is decided to adopt also new advanced and rapidly developed HEP software (PODIO, DD4hep etc.). The current SCT computing infrastructure includes interactive servers for software development, local batch system, common disk space services, software version control system (https://git.inp.nsk.su), web/wiki (https://ctd.inp.nsk.su), mailing lists.

R&Ds of all detector subsystems are being performed. Most of them are in a quite advanced stage; some works are being performed by international groups, for instance, two INFN groups are involved in R&D for the inner tracker and drift chamber; a group from Giessen U. is involved in R&D for the particle identification system. R&Ds of accelerator and collider are going on in active communication with the FCC-ee community.

Implementation of the SCT factory project certainly leads to many scientific, engineering and software development challenges, as any state-of-the-art experiment in particle physics. That is why the key requirement for the successful development, construction and commissioning of the SCT project is a coherent effort of the world-wide community and particularly European researches as the core of this community.