Cremlin Connecting Russian and European Measures for Large-scale Research Infrastructures

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As foreseen in the CREMLIN work programme, this Deliverable D7.2 forms the last step of Task 7.1 within Work Package 7. This report follows up on Deliverable D7.1, labelled "Workshop on technical and research challenges of the SCT project, placed in a European and fully international context, synergy of the SCT, FCC-e^+e^- and CLIC projects".

In the framework of this workshop, which took place in August 2016, proceedings documents were submitted for a total of 28 workshop presentations. The proceedings documents cover a broad range of subjects in the domains of:

- Accelerator design and technologies;
- Detector design and technologies;
- Physics and computing.

The proceedings documents were peer reviewed by senior experts from both BINP and CERN. The proceedings book contains a total of 248 pages. It is published in the "CERN Proceedings" series and should be cited as:

Proceedings of the CERN-BINP Workshop for Young Scientists in e^+e^- Colliders, Geneva, Switzerland, 22 – 25 August 2016, edited by V. Brancolini and L. Linssen,
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The proceedings contain a wealth of information on future e^+e^- colliders, thereby establishing a comprehensive overview report on technological requirements and R&D progress. In order to link the European and world-wide know-how to the new generation of the highly efficient lepton colliders, an executive summary was written and is reproduced on the following pages of this deliverable report.

Executive Summary

"Overview on technological requirements and R&D progress, linking European and worldwide know-how to the new generation of highly efficient lepton colliders"

The Super Charm-Tau factory (SCT) at BINP, Novosibirsk is designed as a low energy electron-positron collider with unprecedented high luminosity of $0.5 - 1 \cdot 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at a centre-of-mass energy between 2 GeV and 5 GeV with possibility to exploit longitudinally polarized electrons at the interaction point (IP). The main aim of the SCT project is the study of charmonium and tau-lepton physics. SCT will provide excellent possibilities for search of new physics and for high-precision measurements of known phenomena. It is essential to create an overview and identify synergies and complementarities between the various lepton colliders worldwide, in particular those under development at CERN, in order to maintain a global basis for the SCT collaboration.

Other lepton colliders operating or planned are CLIC and FCC-ee at CERN, BEPC II and CEPC in China, SuperKEKB and ILC in Japan and DAFNE in Italy LNF/INFN. Despite the fact that all these facilities have different energy ranges (from 0.5 GeV per beam at DAFNE, up to 1 TeV at ILC and 3 TeV final energy at CLIC), different sizes (from 100 m for DAFNE up to 100 km for FCC-ee), different configurations (linear versus circular) and luminosities differing by orders of magnitude, there are still many similarities in the collider designs. The reason is that all these colliders operate at the cutting edge of accelerator physics and technology to achieve their superior performance and therefore they should all use the most advanced solutions.

The Novosibirsk SCT factory will apply a Crab Waist collision scheme (originally proposed in 2006 by Pantaleo Raimondi for the Italian SuperB factory) with a large crossing angle, a large Piwinski parameter and low emittance beams. A novel collision technology was extensively studied and implemented at DAFNE, and the experience of the Frascati ϕ-factory is of great importance for the SCT project realisation. Generally, the same approach is used for DAFNE (where it is called a nano-beam scheme) and FCC-ee. The major features of the lepton colliders stipulating a basis for synergetic collaboration with SCT are listed below:

- An extremely low vertical beta function at the IP (1 mm for FCC-ee and SCT and 0.3 mm for SuperKEKB) and, consequently, a very high vertical beta in the first final-focus quadrupole (up to several kilometres) result in the same problems for all three factories with local chromaticity correction and dynamic aperture and momentum acceptance limitations. The very high beta function in the final-focus quadrupoles requires low nonlinear contents of the quadrupole field, high production accuracy and tough tolerances for assembly and alignment.

- Crab Waist beam-beam effects for high-density colliding-beam studies require fast and effective simulation codes. One of the most popular and widely used codes to explore the beam-beam effects in colliders and to optimize the luminosity is called LIFETRAC. It was developed at BINP and presently it is intensively used at DAFNE, SuperKEKB and FCC-ee. Another popular program was developed at KEK in Japan and is frequently used for crosschecks. The powerful CERN computer cluster is required for this sophisticated and time-consuming computation.

- One of the critical parts of Crab Waist colliders is their final-focus arrangement. Due to the extremely low vertical beta at the IP, the first quadrupole is located closely to the IP inside the detector area. A design of the extremely compact high-gradient (up to 100 T/m) quadrupole magnet is a challenging task. Presently the BINP design of the double-aperture final-focus quadrupole with iron yoke, originally proposed for SCT, is also considered as a possible candidate for the FCC-ee final-focus magnet. Another option based on double-helix superconducting coils was suggested for the Italian SuperB factory and is also studied at FCC-ee and SCT.

- Concerning the machine-detector interface (MDI): the final-focus quadrupole magnets inside the detector volume, the detector solenoid, the anti-solenoids to compensate the solenoid field, as well as the detection equipment (such as the luminometer) render the interaction-region design very complex for both FCC-ee and SCT. Nevertheless, despite the fact that ILC and CLIC are linear colliders, their MDI region with strong quadrupole magnets, solenoid system and local compensation of the IP chromaticity is very similar to the MDI region of circular super-factories, providing a good example of synergetic design and complementarity.
- Another topic common to SCT, FCC-ee and SuperKEKB relates to the high beam current. For SCT and FCC-ee (at the Z-pole energy) the total beam current in each ring is about 1.5 A while for SuperKEKB it exceeds 2 A. High current effects, including beams interacting with their environment, cause lots of dangerous collective instabilities, ion clouds (in the electron ring) and electron clouds (in the positron ring), as well as the heating of vacuum components by the RF bunch field. These effects were carefully studied at PEP (SLAC, USA), KEKB and DAFNE. Unfortunately at BINP the maximum current circulating in the electron-positron colliders is smaller (around 0.5 A). Therefore, relevant assistance to the SCT project in the domains of theoretical calculations and simulations, low-impedance vacuum duct design, HOM free RF cavity design and fast-feedback system development would be extremely useful.
- Due to their high luminosity all the future lepton colliders require intensive and efficient electron and positron sources. The laser driven RF electron source is one of the key elements for such future electron-positron colliders. Similar electron guns with high productivity and beam quality (emittance, stability, energy spread) are necessary for modern synchrotron light sources and free electron lasers. Therefore the relevant laboratories could contribute to the SCT project in the area of electron gun development.
- There is another good example of the synergy between future circular e^+e^- colliders and the light sources. The Crab Waist concept requires beams with very low emittance (the FCC-ee vertical emittance at 45 GeV is 1 pm). This is also an intrinsic feature of light source storage rings. Possible collaboration between the European synchrotron light facilities (ESRF, SOLEIL, PETRA III, MAX IV, etc.) and the Novosibirsk SCT factory (as well as with the CERN FCC-ee project) could be very promising and fruitful. Accurate energy calibration is essential for the FCC-ee experiments at Z and WW centre-of-mass energies. It is planned to measure the Z-boson mass at FCC-ee with an expected statistical accuracy of $\sim 2 \cdot 10^{-6}$ for precise tests of the Standard Model. For this purpose the resonant depolarisation technique, which provides the most precise beam-energy measurement, will be used at FCC-ee. BINP is one of the world leading laboratories exploiting the resonant depolarisation method for beam energy calibration. Presently BINP has a record relative accuracy of the beam energy determination of $\sim 10^{-6}$ at the VEPP-4M collider. The BINP team collaborates with the FCC-ee project for the beam energy measurement by resonant depolarisation or by other methods, such as Compton backscattering or magnetic spectrometers.

Finally we mention briefly some examples of other accelerator technology aspects, which might form a solid basis for collaboration between the SCT factory and other modern electron storage rings (colliders and light sources):

- precise magnets with high-quality magnetic field;
- vacuum chambers with coatings and/or surface treatments to suppress electron clouds;
- superconducting RF systems and solid-state RF generators;
- beam-position monitors with approx 1 μm accuracy;
- control system software based on the EPICS or TANGO platforms.

Concerning synergies in the design and technology development for the physics experiments at the various e^+e^- colliders mentioned above, the situation can be summarised in a similar way. Comparing experiments at SCT in Novosibirsk, CLIC and FCC-ee at CERN, BEPC II in China, DAFNE and ILC in Japan and DAFNE in Italy, there are large overlaps in technology considerations despite the different energy ranges. The BES III detector at BEPC II and the KLOE detector at DAFNE have collected data since several years. The BELLE II detector at SuperKEKB is currently under construction, while future detectors at SCT, ILC, FCC-ee, CEPC and CLIC are in a design and technology development phase. As the most advanced technologies are of prime interest for the following discussion, we concentrate on the experiments currently in a construction phase or in a design and technology development phase. The corresponding facilities aim for high luminosities in the range of $10^{34}\,\mathrm{cm^{-2}s^{-1}}$ to $10^{36}\,\mathrm{cm^{-2}s^{-1}}$, depending on the collider energy. As $\mathrm{e^+e^-}$ colliders are inherently very accurate physics probes, ultimate accuracy is also required for the design and technology choices of the experiments.

As a result, the detector requirements can be summarised as follow:

- excellent momentum resolution for charged particles;
- good energy resolution for photons an electrons (flavour factories) as well as for jets (high-energy colliders);
- ultimate particle-identification capabilities (flavour factories) or good particle-identification capabilities (high-energy colliders);
- excellent flavour-tagging capabilities;
- digitisation and data acquisition systems capable of recording and transmitting data at high rates;
- a high-performance trigger system, required at high-luminosity flavour factories or CEPC/FCC-ee operating at the Z pole.

In practice, going outwards from the interaction point, the experiments are composed of:

- a thin vacuum chamber, typically beryllium of 0.6 mm to 1 mm thickness in the central detector region. In the case of flavour factories and circular high-energy colliders the vacuum chamber includes a thin inner metal layer (e.g. gold, copper) for the absorption of synchrotron radiation or for conductivity reasons related to RF bunch effects;
- a highly accurate vertex detector, located as close as possible to the beam (at radii from 14 mm to 50 mm). The required single point resolution is as small as 3 μm at CLIC and ILC. In the case of CLIC hit time-stamping capability of a few ns is required in order to reduce the impact from beamstrahlung particles. The technology choices for the vertex detector are either thin silicon pixel detectors (Belle II, ILC, CLIC, SCT) or a low-mass TPC (Time Projection Chamber) gas detector (SCT);
- a low-mass main tracker. The most prominent choices for the main tracker are a large drift chamber (SCT, Belle II, FCC-ee), a TPC (ILC, CEPC) or a silicon tracking system (ILC, CLIC, FCC-ee). While the gas detectors offer sizeable low-mass volumes and many measurement points for excellent pattern recognition, the silicon-based tracking option offers the most accurate single point resolution;
- a particle-identification detector system based on aerogel ring-imaging technology (SCT, Belle II) or Cherenkov time-of-propagation technology (Belle II). The need for such highly selective particle-identification systems is specific to flavour factories;
- an electromagnetic calorimeter, based on pure CsI crystals (Belle II, SCT) or CsI(Tl) crystals (Belle II) or based on highly granular particle-flow calorimetry with silicon sensors (ILC, CLIC, CEPC, FCC-ee) or dual readout calorimetry with scintillating fibres (FCC-ee, CEPC);
- a hadron calorimeter based on highly granular particle-flow calorimetry using scintillator tiles as sensors (ILC, CLIC, FCC-ee, CEPC) or dual readout calorimetry (FCC-ee, CEPC);
- a superconducting solenoid with a magnetic fields strength ranging from 1 T to 5 T;
- an iron yoke with an embedded muon system. The muon system comprises detectors of large area. Typical technology choices are RPCs or plastic scintillators.

Several of the technologies listed above are forefront detector R&D subjects, exploiting recently developed ideas or are based on technologies, which have become available only recently. One example is the TPC using modern micro-pattern gas detector technology. Micro-pattern gas detector structures, GEM or Micromegas, provide several advantages over traditional wire planes. They offer high-gain signal amplification with superior rate capability as well as new schemes for reducing ion backflow, allowing the TPC to be read out in continuous mode. Moreover they offer superior spatial resolution and allow for more flexible geometries compared to traditional wire planes. So far, the operational experience with TPCs based on GEMs or Micromegas in collider experiments is still limited. Large R&D efforts are ongoing in preparation for such TPC detectors for the upgrade of the ALICE experiment, for the PANDA experiment at FAIR and for the ILD experiment at ILC. BINP has built and operated GEM detectors for the tagging system of the KEDR experiment and for the VEPP-3 deuteron facility. Moreover BINP is developing GEM-based TPCs for the upgrade of the CMD-3 experiment and for SCT. These developments efforts involve ongoing broad international cooperation.

Another example is the novel ring-imaging aerogel technology, such as the multilayer focusing aerogel RICH (FARICH) for SCT. It is able to provide high μ/π separation below 1 GeV/c and excellent $\pi/K/p$ separation for high momentum particles. At SCT the Cherenkov photons will be detected by silicon-photomultipliers (SiPM). About a million SiPM will be needed for FARICH. The high-energy e^+e^- colliders ILC, CLIC and FCC-ee foresee a similar number of SiPM for their fine-grained hadron calorimeters with small scintillator tiles as the active medium. SiPM development and mass production are therefore a prominent example of synergy, where Russian producers are already playing an important role.

Numerous examples of the e^+e^- accelerator and detector concepts and technologies listed in this summary are described in more detail in these proceedings.

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(On behalf of the Organizing Committee)