The 2021 CEPC International Accelerator Review Committee

Review Report

May 19, 2021

Overview

The CEPC International Accelerator Review Committee was held remotely due to the Covid-19 pandemic on May 11th and 12th 2021. This is the second IARC meeting.

The Circular Electron Positron Collider (CEPC+SppC) Study Group, currently hosted by the Institute of High Energy Physics of the Chinese Academy of Sciences, completed the conceptual design of the CEPC accelerator in 2018. As recommended by the CEPC International Advisory Committee (IAC), the group began the Technical Design Report phase for the CEPC accelerator in 2019, with a completion target year of 2022. Meanwhile an International Accelerator Review Committee (IARC) has been established to advise on all matters related to CEPC accelerator design, the R&D program, the study of the machine-detector interface region, and the compatibility with an upgrade to the t-tbar energy region, as well as with a future SppC. The first IARC meeting took place in Beijing during the CEPC international workshop on Nov. 18-21, 2019.

The charge for the Committee from the CEPC(SppC) team is the following:

1. For the TDR, are the CEPC accelerator design optimizations at different operation energies carried out in a consistent way? Is the TDR work on track?

2. Are there any key technologies not covered by the CEPC accelerator R&D program?

3. How should we proceed with the EDR?

4. The European Particle Physics Strategy Update (EPPSU) was released in June 2020, which places the e^+e^- Higgs factory at the highest priority for the next future facility. In the US the Snowmass process has begun. How do we coordinate and collaborate with international scientists and with other projects such as FCC and ILC, in the areas of accelerator design and R&D?

Answers to the charges

1) Are the CEPC accelerator design optimizations at different operation energies carried out in a consistent way? Is the TDR work on track?

The IARC recognizes that in the TDR design phase, the CEPC team is making strong and ongoing efforts to produce a new baseline using the new High Luminosity parameters. The collider, booster and linac injector work is moving forward in a consistent way towards this, as the Committee noted in this meeting. This will need to be evaluated and approved at future meetings depending on the state of maturity reached. A secure database with appropriate change control to store the current baseline accelerator parameters, which is used by all groups working on the project, would be useful.

2) Are there any key technologies not covered by the CEPC accelerator R&D program?

As stated by the CEPC team, the goal of the TDR is to have a consistent set of parameters describing the accelerator system design with key technologies in hand, with prototypes and site-dependent designs for civil-engineering implementation that will guarantee that the CEPC Engineering Design Phase will begin on a solid foundation in preparation for the launching of construction. Some key R&D items, such as SCRF cavities, cryomodules, 650MHz high-power and high-efficiency klystrons, vacuum chambers, magnets for the collider ring and booster, SC magnets, linac components, instrumentation, electro-magnetic separators, etc. have made substantial progress. More R&D items will be conducted within the current R&D budgets, such as collimators, MDI RCV, injection/extraction kickers and septum magnets, etc. A large number of prototypes are in progress, the completion of which by 2022 represents a challenge with respect to the TDR timeline. On the basis of the presentations, the Committee is of the opinion that most of the key technologies are under appropriate investigation in the TDR program.

3) How should the team proceed with the EDR?

A three-year EDR phase is included in the schedule following the TDR, in advance of construction start. The introduction of such a preparation phase was recommended by the IAC in November 2020.

The TDR is expected to provide a detailed technical description of the CEPC integrated design and parameters including the detector interfaces, the R&D

programme and results for all key parts (in terms of performance and/or costs and risks), and an initial design of the technical infrastructure for the accelerator. Civil engineering studies will also be included.

However, several activities will require further work before construction can start, some of which will require larger engineering resources and a well defined site (i.e. a site selection) for detailed site development and site-specific engineering studies. At least partial project approval is likely to be necessary to enter this phase of the project, based on the TDR.

Some examples of activities that naturally extend into the EDR phase are:

1) Technical design of key parts. This will in many cases be followed by detailed technical design suited for industrial production and pre-series (gradually developed through TDR and EDR) - we saw examples of plans going for example to 2026 for SRF;
2) Integrated studies for performance, parameters and operation: beam-dynamics, lattice and machine parameters, alignment/stabilites, timing, instrumentation specs and solutions, vacuum specs and systems, collimation and shielding and associated radiation studies, operation modes and transitions, reliability. Many of these studies will be carried out for the TDR, but will be improved in the EDR phase;
3) Technical integration studies and specifications for infrastructure: controls, machine protection, basic infrastructure such as Cooling and Ventilation, electricity, gas and fluid systems, safety and access systems, radiation studies and zoning, installation sequences and procedures on surface and underground, transport and handling, dumps and associated safety, integration with detectors, computing and controls, caverns and their infrastructure, etc. Many of these studies are site specific. Initial concepts and studies are needed during the TDR phase, but much more work is necessary in the EDR phase for the selected site;
4) Cost, overall schedule, power consumptions are all needed in TDR, but will be refined and re-evaluated during EDR phase with pre-series and more detailed site-specific design;
5) Specifications of in-kind contributions and agreements can mostly be done in the EDR phase when there is a clear indication of project approval;
6) Civil-engineering studies and site preparatory work, lab layout, access to land, environmental studies and permits, site infrastructure specs, from Civil Engineering, to power, to roads, must be specified. An integrated schedule for the chosen site with accelerator and detector schedules must be drawn up. This will be mainly detailed in the EDR phase, as it is intimately linked to approval and site selection.

There are also a number of similar issues for the detector parts and their integration into the accelerator and laboratory facility; it is very likely that many of these detector integration activities will only be possible in the EDR phase.

A detailed plan for the EDR phase can only be made with knowledge of the site, the likely available resources and personnel.

4) How do the CEPC team coordinate and collaborate with international scientists and with other projects such as FCC and ILC, in the areas of accelerator design and R&D

The Committee welcomed the international mini-workshop on MDI that was organized by J. Gao, M. Koratzinos, T. Tauchi, and held in Jan. 20-22, 2020, at the HKIAS (http://iasprogram.ust.hk/hep/2020/workshop_accelerator.php).

Other international collaborations will hopefully regain momentum once the Covid-19 pandemic is over. As an example of international collaboration, the Committee recommends closer collaboration with SuperKEKB in the design of the Interaction Region, in particular of the IP magnets which are crucial to the achievement of the luminosity performances.

The Committee suggests that international experts in the field could be involved in reviewing specific key topics in detail.

General comments

The meeting was held remotely, and due to the commitments of the IARC members only 2 half days could be reserved for the presentations (11 talks in total), which were proposed by the CEPC team. This has of course limited the amount of information available to the IARC. However additional information could be found in the presentations to the CEPC Workshop held in October 2020 and available at:

https://indico.ihep.ac.cn/event/11444/other-view?view=standard#20201026.detailed

Nevertheless, the Committee realises that a review as detailed as that carried out in 2019 was not possible and looks forward to a more detailed review once face-to-face meetings can resume.

The Committee congratulates the CEPC team for the work performed in the last months and presented at this meeting. The Committee is grateful that slides were uploaded the day before the meeting, allowing the Committee to preview them. The presentations showed that a big effort has been carried out in the last 18 months, in spite of the Covid-19 pandemic.

An upgrade to be able to operate at the t-tbar energy and High Luminosity parameters at all energies, were presented as the new baseline of the project. A large number of prototypes have been designed and are under construction.

The MDI topic was a concern for the IARC in 2019. This seems to be addressed now with the formation of a joint MDI working group in 2020 under the leadership of X. Lou, J. Gao and J.C. Wang. The first MDI meeting was held on August 28-29, 2020, at IHEP Dongguan Branch, China.
(https://indico.ihep.ac.cn/event/12324/other-view?view=standard).
A second MDI meeting will be held on June 16-17, 2021, also at IHEP Dongguan Branch, China.

For the next IARC meeting, hopefully to be held in person, the Committee would like to suggest having a full workshop covering all aspects of the project, in which the number of studies and developments is increasing. As suggested in the previous report (2019), a first day could be dedicated to special topics selected by IARC, then a 3-day workshop covering all other aspects. At least a full day should be reserved for the Committee to discuss and write the report.

The Committee requests that the recommendations given in this 2021 report be addressed and reported to IARC for review two months before the next meeting takes place, in order to allow remaining concerns and questions to be addressed during the first day of the meeting.

In the following, findings and comments for each talk presented to the Committee are given.

Report on Presentations

1. Status Overview of CEPC Project (Xinchou Luo)

The Committee was impressed by the substantial work that has been carried out and summarised in this talk. The majority of the talk will be dealt with in the detailed comments in other presentations. Here the Committee notes only one or two general points presented in this talk.

The Committee was pleased to note that the conflict between the luminosity the machine could deliver in the Z running and the desire of the experiments for a high solenoidal magnetic field was being addressed. The statement that the experiments could easily run in a 2T mode for the Z running rather than the normal 3T was welcomed. The Committee noted that the revised yoke shape means that the magnetic field is much less flat in the region of Q1a, Q1b than previously.

The question of site selection was mentioned several times during the presentations. In particular, the transition between a TDR phase and the EDR phase can only take place after the selection of a site, since final engineering drawings must relate to a specific site. The Committee was reassured that provided everything was well documented, the government's known priorities for regional development were taken into account, and central government was always kept up to date as the process progressed, there was a good chance that a process leading to a site selection could be carried out that would not be overruled by government or funding authorities.

Overall, the Committee was concerned that the current timeline of the TDR and EDR phases may be too tight. The EDR phase needs to start after both site selection and the availability of sufficient funds to go from prototypes to short-series to final production.

Recommendations:

1. ***A secure database with appropriate change control should be introduced to store the current baseline accelerator parameters, which is used by all groups working on the project;***
2. ***Continue to study the influence of the detectors on the luminosity in the Z running and ensure good contact between accelerator and detector experts;***
3. ***Ensure that the government is well informed and supportive of the evolving site-selection process;***

4. ***Monitor progress in the TDR phase, deferring current time-scale milestones if necessary to ensure the optimum progress is made in each phase of the project, given the available resources for prototyping, short-series production of components etc.***

2. CEPC Accelerator TDR Status (Yuhui Li)

The Committee is pleased to see the progress with the CEPC TDR preparation not only in the sense of the CDR expansion and including more details but also in providing higher performance (luminosity increase, t-tbar energy option, electron beam polarization) of the collider in order to meet richer physical goals. A 64-slides report covers three main topics including Hi-lumi upgrade of CEPC, review of key technology R&D results and the facility construction issues (site, civil engineering, timeline, etc.).

To reach higher luminosity, the collider parameters and components (IR magnets and vacuum chamber, sextupoles, RF staging scheme, etc.) were optimized more carefully avoiding extremes. The TME cell was implemented in the booster synchrotron design, providing a reduction in horizontal emittance by a factor of two. The linac energy was increased from 10 GeV to 20 GeV. Optimization results confirm the feasibility of the design and high performance of the collider. R&D components such as arc magnets and injector are compatible with ttbar and Hi-lumi operation.

However, it is not clear which collider model was used for simulation and optimization. For instance, it was recently found that combined study of beam-beam effects with impedances for high-energy Higgs factories causes beam instability and luminosity degradation. This effect was not discussed in the presentation. Some other issues remain, such as the capability to inject enough beam current for the Hi-lumi Z run, the 20 GeV Booster lattice choice, emittance tuning with errors and dynamic aperture with errors for all configurations, which must give enough space for injection in all modes.

An impressive list of the key components including 650 MHz high-efficiency klystron and SC accelerating system, double-aperture magnets for collider, low field precise magnets for booster synchrotron, vacuum chambers, electromagnetic deflector, etc. was presented.

A large number of prototypes are in progress and most of them will be ready by the end of 2022. An increase of human resources is definitely needed to meet this challenging plan. The consequences if the TDR is delivered at the end of 2023 should be addressed.

The CEPC site-selection status was discussed and the project timeline was presented. However, natural and industrial seismic activity was not considered in the talk. Meanwhile, it is known (from synchrotron light sources study) that tens of nanometer of ground vibration amplitude may substantially increase the vertical beam emittance and degrade luminosity. The large size of the CEPC with respect to the typical seismic ground waves means that the stability of various collider properties will be reduced compared to smaller light sources.

The Committee notes that the table of parameters presented here does not agree with the one presented in the Collider Ring Design talk #3. Also confusing is the nomenclature of the IP magnets, sometimes called QD0 and QF1, sometimes Q1a/Q1b, Q2.

Recommendations:

1. ***Provide and present luminosity optimization and beam-dynamic simulations involving more effects (impedances, beamstrahlung, nonlinearities, beam-beam effects, etc.);***
2. ***Since acceleration of the vertically polarized electron beam in the booster synchrotron is considered, the source of the polarized electrons with sufficiently low emittance should be described at least in outline;***
3. ***Consider more extensive international collaboration in development of numerous prototypes and test facilities;***
4. ***Consider seismic vibration influence on the CEPC vertical emittance and luminosity optimization.***

3. Status of CEPC Collider Ring (Yiwei Wang)

The IARC appreciates the progress on the design, in particular to obtain the full extendability of the collider ring to the ttbar energy and the Hi-Lumi operation at the Z. The IARC would like to endorse the direction and encourage the group to go further in detailing the design.

- A new lattice with lower IP beta-y and smaller emittance, larger dipole filling factor to minimize synchrotron radiation was presented. Optimization of the quadrupole radiation effect and a better correction of the energy-dependent aberration were performed. For the optimization of the momentum acceptance, the main aberration is the chromatic second order in the arcs. To correct this, the number of sextupoles has been doubled, also reducing the sensitivity to errors.

Also the position of the sextupoles has been optimized between the two adjacent rings.

- The length of the first drift from IP (L*) has been decreased from 2.2 to 1.9 m, without changing the position of the cryomodule.
- The final quadrupoles are split into a few slices to assure the best focusing at all energies.
- A larger beta-x at the injection point (from 600 to 1800 m) will increase the efficiency, together with a reduced emittance of the beam from the booster (from 3.6 to 1.5 nm), so that the DA requirements can be relaxed to 8 sigma-x, needed for on-axis injection at the Higgs.
- A new round beam pipe was chosen in place of the elliptical one, due to the e-cloud instability threshold.

The IARC still has several questions and concerns on the design:

- The dynamic aperture of the presented lattice should be compared to the previous versions (eg. in 2019) at each energy to see the difference and progress;
- The DA performance with errors is only shown for Higgs energy. All simulations should be performed with 100 micron displacement errors also in the IR since this is what the mechanical group can guarantee;
    - The presented DA with errors shows a strong asymmetry in Dp/p. It may indicate that the optimization is not yet complete;
- The IARC was not convinced by the proposed swapping injection scheme proposed for higher energies. Replacing a full intensity bunch with that from the booster may cause several issues due to possible mismatch of the orbit and phase space between the collider and the booster, especially considering the strong beam-beam effect. The beam from the booster cannot have the same shape for the beam-beam, then transient beam blowup will be unavoidable for both e+e- bunches;
- Other possible injection schemes such as on-axis injection with dispersion at the injection point may work even with the small transverse DA;
- The total diagram for the injection is not clearly presented for all energies:
    - They seem to have injections from scratch without collision, but up to which intensity?
    - How are the beams brought into collision - and how are they separated?
    - Is such a collision-less injection necessary? Many colliders including TRISTAN, PEP-II, KEKB, SuperKEKB did not need it.

    The transition at starting the collision will be very dangerous and cause many transient effects due to the beam-beam interaction;
    - The consistency with the injector performance is not clearly shown;
    - The allowable bunch-charge imbalance in the collider must be consistent with the filling scheme and the beam lifetime in the collider at each energy.
- It is not clear if the lattice includes the 3T detector solenoid with the different field profile and the new anti-solenoid. They may use 2T at Z and 3T at higher energy, but it must be established and stated explicitly;
- Investigation on possible beam instabilities in the Hi-Lumi version has not been presented;
- Strong-strong beam-beam simulations were not shown;
- The number and location of the beam dumps should be optimized to minimize the possible damage to each detector. Probably the nearest possible locations upstream of each detector is optimal.
- The possible jitter of kickers proposed to give beam separation for the common RF should be investigated since it could lead to beams not colliding.

Recommendations:

1. ***A comprehensive review of the DA for all modes of operation and injection scheme would be useful;***
2. ***Simulations of the beam-beam and instabilities for all modes should be presented;***
3. ***The dumping of the beams to protect both detectors should be carefully studied;***
4. ***The injection philosophy should be reviewed and diagrams for the process at all energies should be presented.***

4. Status of CEPC Booster Ring (Dou Wang)

A comprehensive description of the progress on the design of the Booster was presented. Due to the Linac upgrade, the injection energy into the Booster was also upgraded to 20 GeV, which allows the sensitivity of the booster dipoles to the earth's magnetic field to be reduced. The final ramping energy was also increased to 180 GeV for t-tbar operation.
Two lower-emittance booster lattices at 20 GeV have been studied: one based on the TME optics with combined dipoles and sextupoles, another on a FODO lattice. The TME lattice has a horizontal emittance reduced by a factor of two with respect to the CDR lattice, and a larger Dynamic Aperture than the new

FODO lattice. However the effect of machine errors seems to reduce the DA more than in the original CRD FODO lattice.
The IARC is concerned by the injection procedure (already addressed in the previous section). Is the bunch current enough to fill the collider, taking into account the short beam lifetime at the Hi-lumi Higgs running?
For the Hi-lumi Z operation (800 mA), the Linac should go to 200 Hz if more current is needed in less time, but it is not clear if this option has been studied.
The sawtooth effect at 120 was simulated: the emittance growth is minimal (less than 2%) and the DA is not reduced.
A calculation of the effect of the earth field at 10 GeV was presented; after closed-orbit correction, the DA is improved.

Recommendations:

1. ***The bunch feedback components, especially the feedback kickers and high-power amplifiers, should be optimized to give the required narrower feedback bandwidth of the booster ring;***
2. ***It would be useful to have a timeline of the injection complex from the e- gun to the full current collider at each operation energy both for on-axis and off-axis injection;***
3. ***The choice of the final lattice should be done soon, taking into account the injection/extraction parameters at all energies, but also the DA requirements including errors, which is of paramount importance to give efficient injection, ramping and extraction. The design of the booster magnets will also depend on it;***
4. ***For high current Z operation the option of bypassing the baseline RF system with a different one might be considered.***

5. Status of CEPC Linac (Jingru Zhang)

In the CEPC CDR (November 2019) the baseline linac design was formulated as a 10 GeV S-band linac.
The 20 GeV S&C band linac and the plasma wakefield accelerator were discussed as two alternative schemes.
According to the study on the booster-ring dipoles, which have large magnetic-field range and a very low field at low injection energy, the baseline scheme of the Linac was redefined as a 20 GeV S&C band linac.
The main differences from the 20 GeV S&C band linac described in the CDR are the following:

- the energy of the electron-bypass transport line (EBTL) was decreased from 4 GeV down to 1.1 GeV (which permitted the requirements for the bending magnets to be reduced),

- the C-band structure is started from 1.1 GeV (instead of 4 GeV), which reduces the total length of the accelerator from 1400 to about 1200 m (the length of the CDR 10 GeV S-band linac); the chicane working as a bunch-length compressor was recalculated for the new energy,

- the EBTL deflection direction was changed from horizontal to vertical (which permitted the tunnel width to be reduced without increasing its height),

- the beam emittance was decreased to 10 nm (instead 40 nm in CDR and 20 nm in CDR alternative scheme) in order to satisfy the Hi-lumi scheme at the Higgs energy.

The progress in the R&D was reported in the following fields.
During the high-power test, the S-band cavity gradient was increased from 20 MV/m (2019) to 33 MV/m. The mechanical design of the pulse compressor was completed; the machining is in progress. The Flux concentrator of the positron source has been made and a high-power test was finished. The obtained magnetic field at the center peak pulse is 6.2 T, which satisfies the requirements with a good reserve.
The mechanical design of the Damping Ring RF cavity was completed by including the input couplers and vacuum pumping system. The damping ring must be updated to accommodate more bunches with the Hi-Lumi option.

***Recommendations** (specific recommendations for the plasma wakefield accelerator option are given in section 10):*

1. ***Establish a consistent injection diagram for the collider, booster, damping ring and linac, covering the t-tbar and Hi-lumi options;***
2. ***More information on the R&D on C-band structures, which was not presented (also not during the October 2020 workshop) should be given and more attention paid to it;***
3. ***Describe the process to optimise the linac design in terms of cost and risk reduction, relating to the higher injection energy reducing the complexity and difficulty of the booster dipole design (iron-core magnets?).***

6. Progress on MDI design (Sha Bai)

The presentation of the MDI design and related studies shows good progress compared to 2019. The activity is now also being developed in the context of a dedicated working group. A first meeting took place at the IHEP Dongguan Branch August 29, 2020, and a second one will be held June 16-17, 2021. There was also an international mini-workshop on MDI at HKIAS in January 2020, which enabled useful exchanges and comparisons with experts from KEK, CERN and other laboratories.

Synchrotron radiation from upstream magnets was shown not to be an issue in terms of power impinging on the central beam pipe under normal operating conditions, especially compared with other sources of heating such as HOM losses. Extreme beam conditions arising for instance from equipment failure causing a beam to be lost are not considered a problem due to their largely transient nature. On the other hand, more likely intermediate situations of continuous larger-than-normal synchrotron radiation due to static or quasi-static orbit distortions in nearby quadrupoles, persistent non-Gaussian transverse tails, e.g. from beam-beam effects, or from imperfect continuous injection conditions, have not been sufficiently taken into account.

The possible needs for emergency dumping of beams are also not sufficiently considered so far, especially in terms of protecting the most sensitive detector components (e.g. the innermost layers of the vertex detector) against suddenly rising secondary-particle rates, resulting for instance from losses in the IR during top-up injections. Emergency dumping of beams will probably also be very important to prevent quenches of the SC final-doublet magnets near the IP. The tolerances on particle losses in the IR should be studied for both cases as input specification to a fast beam abort system, and generally in the context of the collimation strategy.

Particle losses from the collisions have been simulated, and mitigation with collimators has been evaluated. As expected, the main sources are from the zero-degree radiative-Bhabha and pair-production processes. A table is provided with hit densities and fluences from the different sources. However, it is not clear from the presentation to what extent the full detector was simulated to evaluate the impact in terms of background in its different components. Such a simulation seems important to pursue.

A new beam-pipe design with tungsten as the innermost layer to absorb particle losses within the final-doublet quadrupoles was presented, and expected radiation doses from beam-gas bremsstrahlung losses were estimated, showing acceptable levels over the years of operation. These calculations should also include zero-degree radiative-Bhabha and pair-production losses.

A detailed thermal calculation of the central and forward beam pipes in the presence of HOM power losses including a new design with an enlarged cooling channel shows promising results. The obtained temperature at the equilibrium for the most difficult case (Hi-Lumi Z) seems alarmingly high, and some checks and benchmarking of the simulation in a real situation would seem to be important. This will be possible during the initial operation of CEPC, which will be for Higgs production according to the present scenario, where the expected temperature rises are significantly less.

The design of a movable collimator was too briefly reported to understand whether the issues of possible damage from beam loss, or even survivability, have been sufficiently considered. Does the overall design of the collimation require pre-stages of non-linear magnets to reduce the density of beam tails that must be absorbed by physical collimators ? In general, few details were provided on the overall collimation scheme, which is expected to be relatively complex. Is collimation only needed to reduce backgrounds in the detector, or also to mitigate quenches of SC magnets in the IR ? Are both horizontal and vertical collimators needed ?

For the mechanical study of the cantilevered magnet cryostat and its alignment, the MDI team calculated the deformations taking into account only their respective weights. However, the deformation and the displacement of the cryostat are mainly due to the electromagnetic force in the presence of interference between the detector solenoid and compensation solenoid fields. Compared to the situation at SuperKEKB, the force would be over 50 kN. This effect is much larger than that of the component weight. The electromagnetic force should be calculated, and the effect needs to be included in the mechanical and alignment studies for the final doublet quadrupoles.

Besides the analysis of the stiffness of the cantilevered cryostat, the first mechanical vibration modes were also computed for different choices of magnet support mechanisms, showing little variation. According to the simulation, the expected frequencies are relatively low and should not pose severe problems for the stability of the colliding beams, especially taking into account the IP feedback. It might be advisable to cross-check the simulation and review its assumptions with other expert groups working on mechanical vibration analysis for other similar colliders.

Recommendations:

1. ***A full simulation including the detector, to evaluate the impact of beam losses in the IR in terms of backgrounds, should be presented;***
2. ***Heat load for the Hi-lumi Z case should be investigated;***
3. ***A complete scheme of collimation should be presented, including near-IR ones;***
4. ***An IP feedback procedure, needed to keep beams in collision and stable luminosity, should be presented;***

5. ***Electromagnetic force with interference between the detector-solenoid field and the compensation-solenoid field should be calculated; the effect needs to be included in the mechanical and alignment studies for the final quadrupoles;***
6. ***If the radiation shielding is required to reduce backgrounds in the detector, then the material used for the shielding will be the heaviest element in the cryostat. The deformation of the cryostat, and the resultant misalignment for the quadrupoles should be studied;***
7. ***A fast beam-abort system is needed to protect the most sensitive components of the detector (e.g. the innermost layers of the vertex detector) from sudden surges in hit rates caused by beam particle losses in the IR. The fast-abort system may also be important to help prevent SC final-doublet magnet quenches.***

7. Progress on CEPC RF system (Jiyuan Zhai)

The IARC was impressed by the substantial progress that has been presented on the CEPC RF Systems. The implementation, recommended by the IARC, of the bypass scheme, which also includes different RF systems and their staging, has been the key element for a new parameter optimization, incorporating the objectives for the different SRF systems of the Booster and the Collider.

Following the bypass scheme and strategy, the RF systems that have been presented are now fully consistent with the new set of Hi-lumi machine parameters envisaged for the TDR. The project staging that postpones the ttbar operation until the end of the project allows 20 years for the most ambitious R&D program which aims to develop single-cell cavities operating at the machine frequency of 650 MHz with an accelerating field of 45 MV/m at a Qo of 4×10^{10}.

Starting from the experience worldwide in the past 10 years, the SRF group has been able to understand details and reproduce with the local industry the best accelerating cavities, sometimes obtaining record performances with a simplified and more reproducible process.

The “CEPC SRF System TDR R&D Plan” that has been presented divided into 3 Phases sounds aggressive but feasible. In particular:

- Phase 1: 2019-2020 (System Design, Component Prototyping) has been completed in spite of Covid-19. High-Q and high-gradient cavity prototypes have been successfully produced and tested, meeting the new CEPC specs. Moreover, the progress on the development and testing of the other critical high-power components, namely HOM and power couplers, moved to the prototype phase. Test results are very encouraging. The large SRF infrastructure, named PAPS, for cavity, coupler and cryomodule testing is on schedule in spite of Covid-19;

- Phase 2: 2021-2022 (System Design, Cryomodule Prototyping) is progressing as planned and by the end of next year two cryomodule prototypes are expected, the short one equipped with 2 high-Q, 2-cell cavities at 650 MHz, the other CW XFEL-like with 8 high-Q 9-cell cavities at 1.3 GHz, both tested and reaching the TDR specs and ready for Phase 3;
- Phase 3: 2023-2025 (Cryomodule prototyping, Mass-Production Preparation) where on the basis of the results on prototypes a complete design review is expected to prepare the mass production. This phase can be considered part of the EDR.

In addition to the successful SRF cavity and power-ancillaries development, the IARC recognizes the impressive work that has been done by the IHEP SRF group and congratulate them for the outstand results obtained so far in the development and successful test of a large variety of critical components which will be crucial for the success of the CEPC project. The large number of data and pictures presented gives a clear impression of the quality of the technical work and of the number of young experts involved. These considerations are also very important to create the conditions needed to host a large global project as will the CEPC.

Last but not least the IARC recognizes the competent effort performed by the SRF group to be properly linked to the beam-dynamics colleagues when developing strategies to handle very high beam current such as those envisaged for HL and Z. Based on the experience at KEK, a counter-phasing scheme has been presented together with promising simulations.

Recommendations:

1. ***Address the topic of HOM couplers for the Booster's 1.3 GHz TESLA-type cavities. The well established existing technology for these cavities uses HOM couplers with a power limit of the order of 1W. Because the Booster must be adequate for all the different machine stages, it is crucial to verify HOM coupler consistency also for the Hi-lumi Z operation mode. Consider the option of bypasses and double RF systems;***
2. ***Continue the successful scheme based on a close collaboration with industry, possibly maintaining and promoting some beneficial competition. The extremely high reliability that is required for the SRF cavities and high-power ancillaries at their***

nominal performances require prompt industrialization of any prototype for a practical confirmation of what has been achieved;

3. ***Never mix the long-term R&D, like the one required for the t-tbar cavities, with the crucial challenging R&D needed to transform the present "world records" into routinely produced industrial components, with a perfectly defined production process and associated quality control;***
4. ***As the Covid-19 pandemic scenario improves, reinforce and extend international collaboration on critical components.***

8. Progress on HTS magnet (Qingijn Xu)

The development status of the high-field SC magnet over 20 T for SppC is reported. Following the recommendation in the 2019 CEPC IARC, the SppC magnet team organized international collaboration by submitting the LOI to Snowmass'21 in the US, and contributing to the High-Field Magnets workshop organized by CERN.

The timeline of this magnet development is shown as "1. Construction of the 1st 10 T SC dipole magnet in 2018, 2. Development of 15 T SC dipole magnet and HTS cable R&D, and 3. 20 T SC dipole magnet R&D with Nb_3Sn + HTS or HTS from 2030". The cable material for the high-field magnet, Iron Based Superconductor (IBS), is selected for reasons of material cost. The expected performance of the IBS cable by 2025 is comparable to Bi-2212. The IBS cable current density in 2025 is expected to be increased by almost 10 times compared to 2019. This expectation is based on the experimental data of the cable short sample taken from 2016 to 2020. The current density in this period was increased by a factor of 5 because of improvement in the manufacturing process of the cable.

The construction of 100-m-long tapes of IBS (Ba122) was achieved via a new fabrication technique. The team built a race-track coil with the cable, and the coil was used as a component of the 10-T dipole magnet. The magnet was successfully excited over 10-T. The mechanical analysis of the coil at 10-T was reported. The transport current of the IBS coil at 10-T reached 86.7 % of the short sample data. The basic cable test results were shown, too. The double pancake coil was successfully operated at 48 A in the 30-T external field. However, cracks observed in part of the superconducting (SC) cores in the bending test of the SC tapes are a problem. The critical current degradation with the number of the coil pancakes was shown. The team plans to apply the IBS cable to the double- aperture dipole magnet made of the block coils because of the larger bending radius of the cable in the SC coil. With the progress in the developments and tests, the construction of a IBS-only 12-T dipole magnet within 10 years is shown as the target challenges for the IBS magnet.

In the R&D of the NbTi+Nb_3Sn dipole magnet, the model magnet generated a magnetic field of 11 T at 4.2 K. The team has scheduled the replacement of the present coil with the mechanically improved coil in 2021 in order to reach 12~13-T. The HTS transposed cable is planned to be used in the development of the 16-T hybrid dipole magnet.

From the R&D road map of the high-field magnet, the team targets the construction of 20 T twin-aperture dipole magnets with Nb_3Sn + HTS or HTS only, of which the field quality is better than 10^{-4}. The IBS cable is applied to the HTS coil in the higher magnetic field. In the accelerator magnet with high field quality, an effect of hysteresis of the superconductor on the field quality is usually reduced by squeezing the superconductor size, like the SC filament of 5 micro-meter on the NbTi strand wire. For the IBS cable, this effort should be included in the R&D road map.

Recommendations:

1. ***In the development of the IBS cable, the stress-strain effect on the superconducting performance should be studied, like in the development of the A-15 superconducting material;***
2. ***For the hybrid high-field magnet, the assembly cost and the risk in the magnet operation from using different materials in one magnet, possibly leading to a quench, should be studied for production of a large number of magnets;***
3. ***In the 20-T magnet R&D, the pressure on the coil and the mechanical stress should be evaluated. Countermeasures against the degradation of the cable performance by the pressure will be required;***
4. ***In the 20-T magnet, the IBS or HTS coil will be used as the coil component in the highest field. In this case, the magnetization of the superconductor will have an influence on the field quality of the magnet. The requirement on the field quality of the magnet should be proposed by the optics group;***
5. ***In general, hysteresis of the magnetic field is largely dependent on the superconductor core (filament) size. For the development of the IBS cable, the study of squeezing the core size should be included for the SC magnet to satisfy the required field quality.***

9. Progress on High efficiency klystrons (Zusheng Zhou)

Very good progress was shown for the 650MHz/800kW CW klystron development. The focus for this development is high-efficiency performance and building up industrial capabilities for manufacturing and tests. 120 klystrons are needed for the collider ring.

A first prototype with design/measured efficiency 65/62% has undergone tests at 800 kW in pulsed mode, reaching 700 kW in CW mode after conditioning.

A high-efficiency design with reduced perveance and weaker space charge effects, 77% 3D simulation efficiency, is being fabricated by a Chinese company (Kunshan Guoli Science and Tech.). It will be manufactured by the summer and tests will then start in the PAPS test stand (Platform of Advanced Proton Source in Beijing). Good progress of the manufacture was shown.

A multibeam klystron RF-design (MBK) is completed, aiming for 80% efficiency (3D simulation). The mechanical design is in progress, as well as for a test-bench.

Additional plans for improving the modulator efficiency by recovering the energy dissipated in the klystron collection stage were shown. Also a Multi-stage Depressed Collector klystron concept is being considered, which can improve the efficiency in the unsaturated region.

Overall, the Committee was pleased by the very good progress both in designs and industrial construction and involvement.

Recommendations:

1. ***Test and evaluate carefully the high-efficiency and MBK designs that already have the capability to reach/approach 80% efficiency, before introducing further changes where the gains are probably less, with added costs and where the increased complexity might affect the reliability;***
2. ***Consider already large-scale production and system-operation challenges (redundancy, tests and installation, lifetimes and replacements, etc) that feed back into the design;***
3. ***The RF sources for the injector and booster should be presented in a future meeting.***

10. Progress on Plasma Injection (Dazhang Li)

The Committee congratulates the CEPC team on building a strong collaboration in this area and on the significant progress made in simulating many of the important questions that must be answered to build a plasma injector for a major collider such as CEPC.

The approach to enhance the electron beam energy of 10 GeV from the RF Linac up to 45 GeV using a plasma wakefield accelerator (PWFA) looks feasible for the CEPC. However, to meet the demanding requirements for CEPC PWFA injectors, such as high charge and low energy spread, there are many challenging tasks, especially for position acceleration. One general comment is that, while the plasma injection simulation is done assuming 10 GeV electron beams from the linac, the linac baseline has now been changed from 10 GeV to 20 GeV. In this case, the transformer ratio can be reduced from 3.5 to 2.5 in current design, which can relax the requirements on the plasma injection system. However, it is important to take the updated beam parameters from the C-band linac into account in the simulations.

Accurate simulation is also very important to optimize machine parameters and tolerances. A “cradle-to-grave” simulation requires integration between the beam-dynamics simulation codes and particle-in-cell (PIC) plasma simulation codes. For beam-dynamics simulation, the coherent synchrotron radiation (CSR) effects at low emittance and high peak-current should be considered. For the PIC code, the enormous computing resources required for optimization and tolerance studies over such long distances necessitates the use of models of reduced complexity.

While much progress on electron acceleration in PWFA experiments, such as high transformer ratio (TR > 5), high efficiency from the driver to trailer bunch (>30%), and energy-spread control using a plasma dechirper have been reported, few experiments has been carried out for the positron acceleration in PWFA since the only facility able to produce them was FACET in SLAC, which is now closed. The advent of the new FACET II facility will give the possibility, within a few years, of carrying out experiments on new methods for positron acceleration such as are proposed by the CEPC group.

Modifying the shape of the electron bunch for the driving beam can increase the transformer ratio for high-efficiency electron acceleration in PWFA. The variation of longitudinal shape of the electron bunch affects the accelerating gradient and the achievable final energy. A tolerance analysis study and possible shaping methods for the variation of the longitudinal shape of the electron bunch at the photocathode gun is necessary. The onset of the hosing instability, which results in poor quality of the electron bunch, must also be considered. Therefore, the longitudinal shaping of the electron bunch with high charge is a critical issue.

The longitudinal shape of the trailing bunch is also very important to minimize the energy spread with optimized beam loading. The trailing bunch needs a shorter pulse length and a trapezoidal shape with a sharp rising front to flatten the accelerating gradient for the lower energy spread. This is also challenging.

In the optimized HTR e- acceleration scheme, the spot size is decreased for both the driver and the trailer bunch. Accelerating an electron bunch of size 4 microns in the linac looks very challenging. An initial spot size of 20 microns in the Linac that can be focussed down after the Linac using a plasma lens would be more realistic. This can also help to fulfill the matching condition and preserve emittance with a low beta function.

The length of the plasma source presented is also challenging. Although AWAKE has commissioned a 10m-long rubidium source and oven, such a long source has not previously been used in electron-beam-driven PWFA, where sources are typically a few cm long. Emittance-matching constraints will require manipulation of the plasma gradient at the ends of the cell. One of the most challenging aspects of the use of a PWFA booster in the injection chain of a major collider such as CEPC is that of reliability and reproducibility of the output beams such that they satisfy the requirements for injection into the booster ring and subsequent acceleration. This cannot be reliably simulated but must be tested in appropriate experiments. Very little is so far known about such issues, although a recent study using LWFA at DESY in the LUX beamline has shown that such operation, at least without tight specification of output beam parameters, is in principle feasible.

Recommendations:

1. ***Update the simulations to use the parameters for the beams exiting the C-band linac, corresponding to the new baseline for the CEPC linac;***
2. ***Propose and schedule appropriate experiments to test the new ideas on positron acceleration at the FACET-II facility whenever positrons become available;***
3. ***Consider how to shape the linac pulses at the photocathode gun in order to optimise the transformer ratio and avoid hosing instability;***
4. ***Consider relaxing the beam-size requirements in the linac and focussing the beam at the entrance to the PWFA stage using a plasma lens;***

5. ***Design and propose appropriate experiments to investigate the stability of the proposed plasma injector over many-hour and several-day periods, necessary to inject and subsequently accelerate beams with the required quality in the booster ring;***
6. ***Consider on what timescale a robust and costed proposal for a plasma injector/booster can be formulated, how it enters into an optimised cost and risk assessment and how it can be matched with the TDR/EDR timescales set out for CEPC.***

11. Progress on IP SC magnet (Yingshu Zhu)

Based on the requirement of the CDR, fabrication of a short (0.5 m) model magnet of QD0 with cos 2θ winding has started. Some components of a winding machine and coil heating and curing system have been fabricated and test winding has started. The R&D magnet with the real SC cable will be completed this year. The excitation test and the field measurement will be performed one year later.

The 2D cross-section design of the QF1 coil is optimized with ROXIE, and the magnetic-field cross talk between the two quadrupoles on the two beam lines was calculated with the two-aperture model with iron yokes. The field quality of the single quadrupole is at the level of 10^{-4} with respect to the quadrupole field. The field cross talk is evaluated to not be a problem.

3D magnetic-field calculations including iron yoke are progressing by ROXIE. The integral field quality of the 3D magnet model is within 10^{-4}.

The compensation solenoid model has been shown. The maximum central field of the solenoid is 6.8-T. The solenoid magnet is designed with a rectangular NbTi conductor. The peak field in the coil is considered to be higher than 6.8-T. This magnetic field is considered to be high for the NbTi cable under the expected design operation temperature. The operation margin of the solenoid magnet needs to be studied.

The load line ratio for each magnet, which is a basic value for gauging the stability of the magnet operation, should be evaluated. In this discussion, the usage of the expected SC cable performance (Bi-2212) is risky. The quench protection should be included in the magnet design. The high current density of the SC cable used requires excellent quench protection if burn out of the cable is to be avoided.

Design considerations for the updated Hi-lumi scheme with L*=1.9 m were shown. QD0 in CDR is separated into Q1a and Q1b. The corrector magnets are designed only for Q1b and Q2 while Q1a has a higher field gradient than Q1b. In the Q1a 2D field calculation, the field cross talk was evaluated between two apertures. The hysteresis influence of the iron in the low field between two apertures on beam operation was pointed out.

Several ideas to cope with the severe requirements including using HTS were presented. The total weight of the finalifocus magnet system is of great concern; several design options were shown. A CCT magnet is considered as an alternative design of Q1a. The engineering current density of CCT is 2670 A/mm^2, and it is 2.5 times larger than that of the cos2θ model. In the report, field profile and field harmonics that meet the requirements were described. From the standpoint of magnet operation, the temperature rise of the SC wire at magnet quench has been studied in a careful way.

The required number and kinds of corrector magnets were not presented. While Q1a is required to generate a 1.7-times higher field gradient than Q1b, Q1a does not have the corrector magnets. A corrector system to cope with assembly errors of the quadrupoles in the cryostat and alignment error on the beam lines should be designed.

The evaluation of the magnetic force between the detector solenoid and the compensation solenoids, iron yokes of the quadrupoles etc. was not presented but it is essential in the magnet-cryostat design. When the compensation solenoids are operated, the magnetic forces push the magnet-cryostat out to the IP, and when a quench of the solenoid occurs, the iron yokes and the magnetic shields are pulled into the IP (negative direction). The force is considered to be over several 10^5 N, and this force deforms the alignment of the SC quadrupoles. In the study, some magnet models have been studied for reducing the magnet weight, but this force will have a much larger effect on the system design.

As mentioned above, the support design of the helium vessel is important. The electromagnetic forces are transferred from the compensation solenoids and the iron yokes to the helium vessels. The vessels are supported with some mechanical structure at room temperature. Therefore, the support design should be performed in a careful way, including the mechanical strength, thermal load and thermal contraction. Estimation of the heat isolation and cooling is needed. As heavy shielding material will be required inside the cryostat to reduce beam background to the detector, excellent communication with the MDI group will be needed.

Assuming that the physical aperture of the vacuum chamber in QD0, especially in vertical direction, is the smallest part in the ring relative to the vertical beam size, the collimation system might introduce restrictions on beam operation.

Recommendations:

1. ***Estimate the electromagnetic force between the detector solenoid and the compensation solenoids, iron yokes of the quadrupoles etc;***
2. ***Evaluate the load line ratio for each magnet;***
3. ***The field cross-talk between the magnets, such as Q1a and Q1b should be estimated and taken into account in the design;***
4. ***Clarify the required number and kinds of corrector magnets. Collaboration with the optics group is essential;***
5. ***Clarify the structure of the cryostat. Collaboration with the MDI group will be needed;***
6. ***Specify the collimator system required to shrink the aperture to protect the QD0 from quenching due to the beam. Collaboration with the MDI and optics group will be needed;***
7. ***Check the solenoid field profile of the detector solenoid along z, which has a large field gradient in the detector, which produces the large electro-magnetic force on the compensation solenoid.***

The 2021 CEPC International Accelerator Review Committee Meeting

Remotely held

May 11th 2021	EU time	Beijing time	Talk time	Speaker	Title
	09:00	15:00	15'	IARC members	Closed session
	09:15	15:15	20'	Xinchou Lou	Status Overview of CEPC project
	09:35	15:35	30'+5'	Jie Gao/ Yuhui Li	CEPC Accelerator TDR Status
	10:10	16:10	25'+5'	Yiwei Wang	Status of CEPC Collider ring
	10:40	16:40	25'+5'	Dou Wang	Status of CEPC Booster ring
	11:10	17:10	25'+5'	Jingru Zhang	Status of CEPC Linac
	11:40	17:40	25'+5'	Sha Bai	Progress on MDI design
	12:10	18:10	30'	IARC members	Closed session
	12:40	18:40			Adjourn
May 12th 2021	09:00	15:00	15'	IARC members	Closed session
	09:15	15:15	25'+5'	Jiyuan Zhai	Progress on CEPC RF system
	09:45	15:45	25'+5'	Qingjin Xu	Progress on HTS magnet
	10:15	16:15	25'+5'	Zusheng Zhou	Progress on High efficiency klystron
	10:45	16:45	25'+5'	Dazhang Li	Progress on Plasma injection
	11:15	17:15	25'+5'	Yingshun Zhu	Progress on IP SC magnet
	11:45	17:45	30'	ALL	Brief discussions, Summary for all talks
	12:15	18:15	45'	IARC members	Closed session
	13:00	19:00			Adjourn
May 19th 2021	09:00	15:00	30'	ALL	Discussions, additional Q&A
	09:30	15:30	150'	IARC members	Closed session for document redaction
	12:00	18:00	60'	ALL	Report presentation
	13:00	19:00			Adjourn

Presentations: The 2021 International Accelerator Review Committee Meeting
https://indico.ihep.ac.cn/event/14295/other-view?view=standard

Committee members:

Philippe Bambade (LAL)

Maria Enrica Biagini (INFN Frascati, chair)

Brian Foster (John Adams Institute, Oxford)

In Soo Ko (PAL)

Eugene Levichev (BINP)

Katsunobu Oide (CERN/KEK)

Norihito Ohuchi (KEK)

Carlo Pagani (INFN Milan)

Anatoly Sidorin (JINR)

Steinar Stapnes (CERN)

Makoto Tobiyama (KEK)

Zhentang Zhao (SINAP)