7 R&D programmes oriented towards specific future facilities

7.1 The FCC-ee R&D programme

7.1.1 Status and main R&D directions

In summer 2021, the Future Circular Collider Feasibility Study was launched [1, 2]. It addresses a key request from the 2020 Update of the European Strategy for Particle Physics [3], which states that "*An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy.*" and "*Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.*"

The FCC-ee builds on 60 years of operating colliding beam storage rings. The design is robust and will provide high luminosity over the desired centre-of-mass energy range from 90 to 365 GeV. The FCC-ee is also the most sustainable of all Higgs and electroweak factory proposals, in that it implies the lowest energy consumption for a given value of total integrated luminosity [4].

The FCC-ee R&D is focused on incremental improvements aimed mainly at further optimising efficiency, obtaining the required diagnostic precision, and on achieving the target performance in terms of beam current and luminosity. FCC-ee will strive to include new technologies if they can increase efficiency, decrease costs or reduce the environmental impact of the project. Key FCC-ee R&D items for improved energy efficiency include high-efficiency continuous wave (CW) radio frequency (RF) power sources (klystrons and/or solid state), high-Q superconducting (SC) cavities for the 400–800 MHz range, and possible applications of HTS magnets. For ultra high precision centre-of-mass energy measurements, R&D should cover simulations and measurements, that both are state-of-the-art and beyond, in terms of spin polarisation and polarimetry (inverse Compton scattering, beamstrahlung, etc.). Finally, for high luminosity, high current operation, FCC-ee requires a next generation beam stabilisation/feedback system to suppress instabilities arising over a few turns, a robust low-impedance collimation scheme, and a machine tuning system based on artificial intelligence (AI). In the following we present more details, describe additional R&D elements, and identify links and overlaps with the Accelerator R&D roadmap.

7.1.2 Recent design changes

The conceptual design report (CDR), published in 2019 [5], described the baseline FCC-ee design with a circumference of 97.75 km, 12 surface sites, and two collision points. In 2021, a further design optimisation has resulted in an optimised placement of much lower risk, with a circumference of 91.2 km and only 8 surface sites, and which would be compatible with either two or four collision points. Consequently, adapting the CDR design and re-optimisation of the machine parameters are underway, taking into account not only the new placement, but also the possibly larger number of interaction points, and the mitigation of complex "combined" effects, e.g. the interplay of transverse and longitudinal impedance with the beam-beam interaction.

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7.1.3 SRF cavity developments

Since Tristan and LEP-2, the superconducting RF system is the underpinning technology for modern circular lepton colliders. The FCC-ee baseline foresees the use of single-cell 400 MHz Nb/Cu cavities for high-current low-voltage beam operation at the Z production energy, four-cell 400 MHz Nb/Cu cavities at the W and H (ZH) energies, and a complement of five-cell bulk Nb 800 MHz cavities at 2 K for low-current high-voltage $\mathrm{t\bar{t}}$ operation [5]. In the full-energy booster, only multi-cell 400 and 800 MHz cavities will be installed. For the collider, also alternative RF scenarios, with possibly fewer changes between operating points, are being explored, such as novel 600 MHz slotted waveguide elliptical (SWELL) cavities [6].

Roadmap R&D work towards superconducting cavities with novel fabrication technology, improved quality factor and high-power couplers described in Section 3.5.1, will benefit FCC-ee. Higher-Q cavities could lower the electric power required for the cryogenics and/or decrease the size of the installation. These positive effects will be noticeable at all operating energies. For FCC-ee, a higher quality factor does not lower the RF power required, since almost all the RF power is directly transferred to the circulating beams.

For the Z running, the beam current is high, impedance and higher-order-mode losses are a concern, and here synergies exist with the cavity development for high-current energy recovery linacs (ERLs) in Section 6.6.2, e.g. R&D on $\mathrm{Nb_3Sn}$-coated cavities. It is worth emphasising that both ERLs and circular colliders, like FCC-ee, require CW SRF systems.

The R&D items listed in the Roadmap Section 3.5.1 “SRF challenges and R&D objectives” are all relevant, and so are the elements listed in Section 6.6.2 “SRF technology and the 4.4 K perspective”. The novel fast reactive tuners mentioned in Section 6.6.3 would also boost the performance of the FCC-ee RF system.

7.1.4 Efficient CW RF power sources

Efficient and compact RF power sources are another key element of the FCC-ee design. The R&D goal is an efficiency higher than 80%, with the aspiration to exceed 90%. In this respect, Section 3.5.3.1 “High-efficiency klystrons & solid-state amplifiers” defines highly pertinent R&D objectives. However, the RF frequencies proposed for the FCC-ee, of 400–800 MHz, are lower than those considered in Section 3.5.3 and some, if not all, of the R&D listed in Section 3.5.3.1 focuses on pulsed RF systems, while prototyping of CW RF power sources in the FCC-ee target frequency range will be required.

7.1.5 R&D for the FCC-ee arcs

Aside from the various RF systems, another major component of the FCC-ee is the regular arc, covering almost 80 km. The arc cells must be cost effective, reliable and easily maintainable. Therefore, as part of the FCC R&D programme it is planned to build a complete arc half-cell mock up including girder, vacuum system with antechamber and pumps, dipole, quadrupole and sextupole magnets, beam-position monitors, cooling and alignment systems, and technical infrastructure interfaces, by the year 2025.

A key element of FCC-ee are the magnets, of rather low field. Constructing some of the magnets in the FCC-ee final focus or arcs based on HTS technology could lower energy consumption and increase operational flexibility. The thrust of this HTS R&D will not be on reaching extremely high field, but on operating lower-field SC magnets at temperatures much higher than liquid He temperatures (between 40 and 77 K). There could be some potential, perhaps marginal, overlap with Roadmap Section 2.6.1 Part 2 “Demonstrate the suitability of HTS for accelerator magnet applications”.

7.1.6 Beam diagnostics

As experience at previous and present colliders has taught us, adequate beam diagnostics is essential for reaching or exceeding design performance. For this reason, the FCC-ee R&D programme foresees the prototyping of key beam diagnostics, like bunch-by-bunch longitudinal charge-density monitors, ultra-low emittance measurements, beam-loss and beamstrahlung monitors, real time monitoring of the collision offsets, a polarimeter for each beam able to measure the 3D polarisation vector as well as the beam energy, and fast luminometers.

7.1.7 Other R&D and expertise maintenance

New developments for the FCC infrastructure, or at least a preservation of the know-how presently existing at CERN, are also needed in the domains of radiation to electronics, robotics, general energy optimisation, digital mock-up of the machine, survey and alignment, etc.

7.1.8 Polarimetry and centre-of-mass energy calibration

Highly precise centre-of-mass energy calibration at c.m. energies of 91 GeV (Z pole) and 160 GeV (WW threshold), a cornerstone of the precision physics programme of the FCC-ee, relies on using resonant depolarisation of wiggler-pre-polarised pilot bunches [7]. The target precision at the Z pole requires a considerable improvement in the understanding of the relationship between the spin-tune, measured by resonant depolarisation, and the beam energies. This improved understanding must begin by beyond the state-of-the art simulations of the spin dynamics in a machine with misalignments and field errors, including the resonant depolarisation process itself. The reduction and control of the centre-of-mass systematics resulting from the combination of collision offsets with residual dispersion will require the development of novel diagnostics and the associated operational procedures. The operation with polarised pilot bunches requires constant and high precision monitoring of the residual 3-D spin-polarisation of the colliding bunches which would affect the physics measurements. This topic is one of the challenging branches of the accelerator physics R&D for FCC-ee.

7.1.9 Monochromatisation

In addition to the four baseline running modes, on the Z pole, at the WW threshold, at the (Z)H production peak, and above the $\mathrm{t\bar{t}}$ threshold, another optional operation mode is presently under investigation for FCC-ee, namely the direct s-channel Higgs production, $\mathrm{e^+e^-} \rightarrow \mathrm{H}$, at a centre-of-mass energy of 125 GeV. Here, a monochromatisation scheme should reduce the effective collision energy spread so as to become comparable to the width of the Higgs [8]. The monochromatisation scheme, never implemented in any operational collider, requires further accelerator design efforts, which could be implemented in dedicated accelerator beam studies at a suitable facility. The development of the dedicated diagnostics required for the success of this most challenging endeavour will benefit highly from the centre-of-mass energy calibration research discussed above.

7.1.10 FCC-ee pre-injector

Concerning the FCC-ee pre-injector, the CDR design foresaw a pre-booster synchrotron. Now this choice is under scrutiny. As an alternative, and possibly new baseline, it is proposed to extend the energy of the injection linac to 10–20 GeV, for direct injection into the full-energy booster. The S-band linac could be based on state-of-the-art technology as employed for the FERMI upgrade at the Elettra synchrotron radiation facility. The R&D foreseen in Section 3.5.2.2 “NC RF manufacturing technology” could further improve the S-band cavity performance and fabrication methods, and lower the cost of this linac.

It is also envisaged to design, construct and then test with beam a novel positron source plus capture linac, and measure the achievable positron yield, at the PSI SwissFEL facility, with a primary electron energy that can be varied from 0.4 to 6 GeV.

Should the relevant developments listed in Sections 4.6.4 and 4.6.5 be successful, then a low-emittance plasma based electron source and plasma injector linac might reduce the size and the cost of the FCC-ee pre-injector. The plasma linac would need to have demonstrated the capability of accelerating positrons at the desired beam current and beam quality.

7.1.11 Full energy booster

The injection energy for the full-energy booster is defined by the field quality of its low-field magnets. Magnet development and prototyping of booster dipole magnets, along with field measurements, should guide the choice of the injection energy.

7.1.12 Lessons from SuperKEKB and beam studies

The SuperKEKB collider, presently being commissioned [9], features many of the key elements of FCC-ee: double ring, large crossing angle, low vertical IP beta function β_y^* (design value $\sim$0.3 mm), short design beam lifetime of a few minutes, top-up injection, and a positron production rate of up to several 10^{12}/s. SuperKEKB has achieved, in both rings, the world's smallest ever β_y^* of 0.8 mm, which also is the lowest value considered for FCC-ee. Profiting from a new "virtual" crab-waist collision scheme, first developed for FCC-ee [10], in June 2021 SuperKEKB reached a world record luminosity of 3.12×10^{34} cm^{-2}s^{-1} [9]. However, many issues still need to be addressed, such as a vertical emittance larger than expected, even at low intensity or without collision, collimator impedance and single-bunch instability threshold, unexplained sudden beam loss without any beam oscillation, insufficient quality of the injected beam, etc.

In view of the SuperKEKB experience, studies of vertical emittance tuning is another important R&D frontier for FCC-ee. This includes simulating realistic beam measurements, constructing optics tuning knobs, especially for the final focus, and developing beam-based alignment procedures for the entire ring. Software development also is an important component of this activity. Effects of beam-beam collisions and monitor resolution limits need to be considered, as should be the impact of machine errors and tuning on the dynamic aperture and on the achievable polarisation levels.

Beam studies relevant to FCC-ee — for example on optics correction, vertical emittance tuning, crab-waist collisions, or beam energy calibration — can, and will, also be conducted at INFN-LNF/-DAFNE, DESY/PETRA III, BINP/VEPP-4M, and KIT/KARA [11].

7.1.13 Concrete roadmap synergies

Considering the different chapters of the Roadmap, we can identify the following items that could help support the FCC-ee performance and/or lower its cost and environmental impact:

- **High-field magnets**: This HFM programme is fundamental for FCC-hh. FCC-ee could also profit if the HTS magnet R&D helped demonstrate the feasibility of lower-field HTS magnets operated at higher temperature, with emphasis on lowering their cost (Sections 2.5.1, 2.6.1 Part 2, 2.6.2, 2.7.3 and 2.7.4). In particular, the answers to questions Q7 and Q8 (Section 2.6.2) would be of interest to FCC-ee ("Q7: Besides magnetic field reach, is HTS a suitable conductor for accelerator magnets, considering all aspects from conductor to magnet and from design to operation?" "Q8: What engineering solutions, existing or to be developed and demonstrated, will be required to build and operate such magnets, also taking into account material availability and manufacturing cost?").
- **High-gradient RF structures and systems**: Higher gradients than today are not the primary interest for the FCC-ee SRF system, but limiting energy consumption and improving accelerator reliability are a common focus. Numerous synergies can be spotted. In particular, the R&D effort on "Thin superconducting films for SRF cavities" (Section 3.5.1.3) is well matched to the needs

of FCC-ee. The R&D on both fundamental and high-power couplers (Section 3.5.1.4) is equally of immediate interest. Higher-efficiency CW RF power sources such as a novel generation of klystrons or advanced solid-state devices (Section 3.5.3.1) are required for FCC-ee; the 200 MHz CW solid-state source example from the CERN Super Proton Synchrotron (SPS) is encouraging. "Technologies to reduce RF power needs for acceleration" (Section 3.5.3.3) and, in particular, the Ferro Electric Fast Reactive Tuner, or FE-FRT (Section 3.5.3.3), might smoothen FCC-ee RF operation when re-injecting the full beam after an abort, although in regular operation with top-up the beam currents are approximately constant. Some of the NC RF development would be relevant for the FCC-ee S-band injector linac, especially improvements on NC RF manufacturing technology (Section 3.5.2.2). Part of the work described in Section 3.5.3.5 on "Artificial Intelligence (AI) and machine learning" for RF operation could potentially overlap with the development of an AI-based machine tuning system for FCC-ee. Adequate technical SRF infrastructure (Section 3.7) is of prime importance for the FCC-ee SRF R&D.

- **High-gradient plasma and laser accelerators**: A plasma based linac could be an alternative to the S-band linac, and reduce cost, provided such a linac can accelerate a positron beam with the desired charge/current and emittance. An ultra-low-emittance plasma source for the electron beam could also be helpful. In this sense, the positron technical demonstrations (2026), work on advanced plasma photoguns (2027), and the development of plasma sources for high-repetition rate, multi-GeV stages (by 2035) (Sections 4.6.4 and 4.6.5) are all of potential relevance to FCC-ee.
- **Bright muon beams and muon colliders**: There is no obvious overlap of this effort with the FCC-ee R&D needs for the next decade.
- **Energy-recovery linacs**: The SRF technology programme for ERLs perfectly matches the needs of FCC-ee (Section 6.6.2). The Roadmap states: "ERL SRF system developments must now focus on – system designs compatible with high beam currents and the associated HOM excitation; – handling of transients and microphonic detuning that otherwise require a large RF overhead to maintain RF stability; – enhanced cryogenic efficiency of SRF modules." All three of these items also apply to FCC-ee. In addition, the CW mode of operation and the RF frequency, e.g. for PERLE, are the same or quite similar. The aforementioned synergies with ERL developments relate to the SRF technology R&D programmes, and not to any use of ERLs as acceleration technology for the FCC-ee. There also is a common interest in FRTs, and there may be several synergies in R&D for novel beam instrumentation, such as non-intercepting diagnostics, beam halo and beam loss monitoring, etc. (see Sections 6.6.4 and 6.8.3).

Prioritising within the five relevant chapters of the LDG Roadmap, several items listed in Chapters 3 and 6 with impact on the FCC-ee RF systems are the most important and urgent ones, namely SRF thin film technology, high efficiency RF power sources, and HOM/fundamental coupler development. At second place appear improved manufacturing techniques for an S-band linac.

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