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THE FUTURE CIRCULAR COLLIDER IN EUROPE*

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Abstract

The proposed Future Circular Collider (FCC) integrated programme consists of two stages: An electron–positron collider serving as a highest-luminosity Higgs-boson, electroweak and top-quark factory, followed by a proton–proton collider with a collision energy around 100 TeV. In 2021, the CERN Council initiated the FCC Feasibility Study. This study covered, inter alia, physics objectives and potential, geology, civil engineering, technical infrastructure, territorial implementation, environmental aspects, R&D needs for the accelerators and detectors, socio-economic benefits, and cost. The Feasibility Study was completed on 31 March 2025. The subsequent European Strategy Symposium has singled out the FCC as the by-far preferred future collider option for CERN. We present a few study highlights, the status, and the next steps.

INTRODUCTION

A circular Higgs factory was first proposed in 2011, after initial hints at a possible discovery from the LHC experiments [2]. This concept was then driven forward in 2012–2013, mostly as a community initiative. In response to the 2013 Update of the European Strategy for Particle Physics (ESPP) [3], in 2014 the global Future Circular Collider (FCC) study was set up. This study, which was partly supported by the EU co-funded EuroCirCol project [4], resulted in four volumes of Conceptual Design Report (CDR), notably volume 2 on the FCC-ee lepton collider [5]. Following the 2020 ESPP Update (ESPPU) [6], the CERN Council launched the FCC Feasibility Study (FS). Like the concept study, the FS was organised as an international collaboration comprising more than 150 participating institutes from around the world. Parts of the FS work were carried out within the EU co-funded FCC Innovation Study [7]. The resulting Feasibility Study Report (FSR) was submitted as complementary input to the 2025/26 ESPP Update [8–10]. It presents a baseline technical design and discusses, as requested, numerous other key feasibility aspects, including tunnel construction, cost, sustainability and environmental conditions.

THE FCC INTEGRATED PROGRAMME

The FCC 'integrated programme' consists of an initial electron-positron collider FCC-ee, which is followed by a proton-proton collider, FCC-hh. This sequence is well matched to the current scientific landscape after 15 years of LHC operation. The proposed staging takes into account: (1) the physics priorities as developed and stated by ESPPU 2013 and 2020; and (2) the relative technology readiness and costs of FCC-ee and FCC-hh. The FCC integrated programme is also aligned with the 2023 US Particle Physics Project Prioritization Panel (P5) recommendations [11].

Both FCC-ee and FCC-hh are installed in the same 91 km circumference tunnel close to CERN. The FCC-hh reuses all the FCC-ee civil engineering and much of the technical infrastructure, thereby maximising the return on investment. The FCC layout features 8 arcs of equal length, 4 technical straights and 4 experimental straights, as is illustrated in Fig. 1. Taking advantage of the four-fold superperiodicity for maximum performance, FCC-ee and FCC-hh each accommodate four detectors. Parameters and luminosity scenarios for the FCC-hh are presented in Ref. [12].

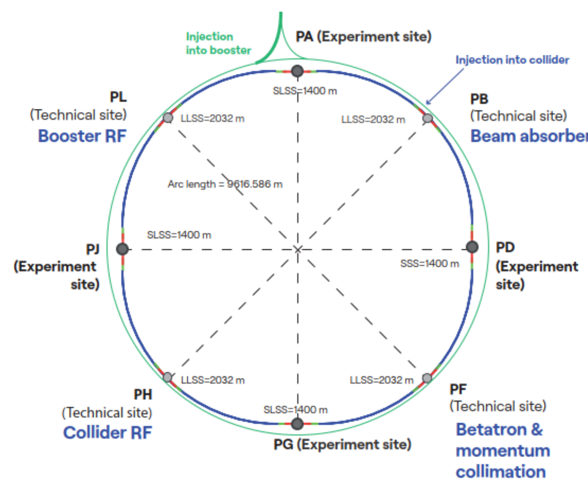

Figure 1: The layout of the FCC-ee, illustrating the four collision points and the four technical insertions [9].

FCC-ee DESIGN AND OPERATION PLAN

For maximum performance, the FCC-ee is conceived as a double-ring collider with separate beam pipes for electrons and positrons, which does not only allow for storing a large number of bunches but also for tapering of magnet strengths to match the local energy of each beam, even with an 'energy sawtooth' due to synchrotron radiation. The luminosity is maximised by regular top-up injection from a full-energy booster synchrotron, which shares the collider tunnel.

The FCC-ee operates at four baseline centre-of-mass energies, corresponding to the Z pole, the WW pair production, the ZH production peak, and the $t\bar{t}$ production threshold, always delivering the highest possible luminosities to four experiments. The main parameters for each FCC-ee mode of operation are listed in Table 1. Both natural bunch lengths due to synchrotron radiation (SR) and collision values including beamstrahlung (BS) are shown in the table. The FCC-ee collider rings feature a combination of 400 MHz

* This title is a modified update of Ref. [1]

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and 800 MHz RF systems, with voltage strengths indicated. For the integrated luminosity, 185 days of operation per year, and luminosity production at 75% efficiency with respect to the ideal top-up running is assumed [13].

Synchrotron radiation power per beam is held constant at 50 MW, which determines the total beam current at each energy. Beamstrahlung noticeably increases the momentum spread and bunch length, especially for the lower-energy running modes. The vertical beta function β_y^* is limited by the length of the geometric overlap region, which itself is determined by bunch length, beam size, and crossing angle. The crab waist scheme avoids coupling the vertical and horizontal betatron motion through the crossing-angle collision, thereby, enabling a high (vertical) beam-beam tune shift and high luminosity. The maximum design value for the vertical beam-beam tune shift, of order 0.1, determines the bunch charge. The arc optics is changed between the WW and ZH running by halving the arc cell length (or by increasing the phase advance) to maintain a small emittance at higher energy. At the Z, the effective RF voltage is lowered by reverse phase operation, while retaining maximum RF power transfer efficiency.

Figure 2 displays the baseline mode sequence [14]. In this baseline model, the sequence of events goes with increasing centre-of-mass energy, but there is a great flexibility in the sequence all the way to 240 GeV. The integrated luminosity delivered during the first two years at the Z pole and the first year at the $t\bar{t}$ threshold is assumed to be half of the annual design value. The hatched area indicates the shutdown time needed to prepare the collider for the higher energy runs at the top-pair production threshold and above. Other sequences are also possible for the first three modes (Z, WW and ZH). Irrespective of the exact sequence, over a time span of 15 years, more than 6×10^{12} Z bosons, 2×10^8 WW pairs, 2.7×10^6 Higgs bosons, and 2×10^6 $t\bar{t}$ pairs are produced. On the Z pole and at the WW pair threshold, the collision energy can be precisely calibrated by frequent resonant depolarisation of pre-polarised pilot bunches. The physics potential is maximised by the deployment of four multi-purpose detectors, with different scientific and cost optimisations, e.g., for Higgs physics, ultraprecise electroweak and QCD measurements, heavy flavour physics, and searches for feebly coupled particles, respectively.

The FCC-ee collider with its injector also offers unique opportunities for numerous other branches of physics and science [15], ranging from the proposed production of true muonium to generating spatially coherent photon beams down to 0.1 Å wavelengths at several orders of magnitudes higher average and peak brightness than any existing or planned light source.

KEY CONCEPTS

By taking advantage of various new design concepts, including the double-ring configuration and a full-energy booster synchrotron, the FCC-ee can deliver 4 to 5 orders of magnitude higher luminosity per unit electrical power than the previous LEP collider (Fig. 3). The key design elements of the FCC-ee accelerator design were all demonstrated in routine operation at several previous or presently operating colliders.

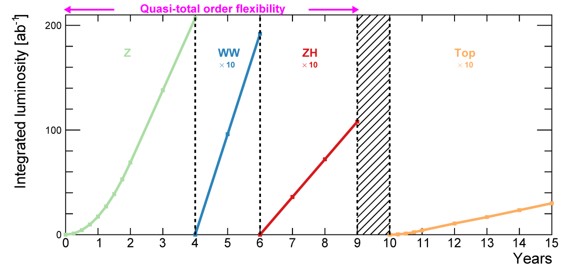

Figure 2: Operation sequence for FCC-ee with four interaction points, showing integrated luminosity at the Z pole (green), the WW threshold (blue), the ZH production peak (red), and the top-pair threshold (orange) versus time.

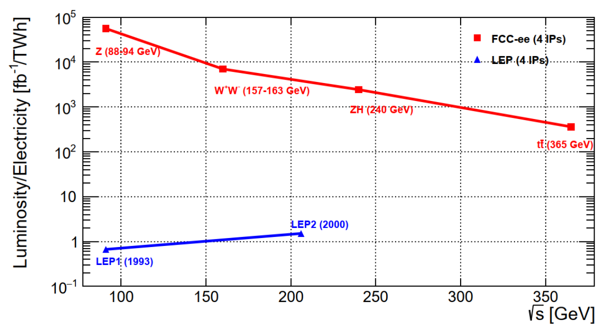

Figure 3: Luminosity per electrical energy as a function of centre-of-mass (c.m.) energy for LEP and FCC-ee [16].

Top-up injection was, or is, successfully applied at several previous or operating colliders, such as KEKB, PEP-II, BEPC II and SuperKEKB, and also at many modern light sources. Beam currents much exceeding those considered for FCC-ee (Z) operation were reached at PEP-II, KEKB, SuperKEKB and DAΦNE, among others.

At all energies, the FCC-ee uses the ‘crab-waist’ collision scheme, following its successful implementation at both DAΦNE and SuperKEKB [17, 18]. The small vertical β_y^* required for FCC-ee, of order 1 mm, has been used routinely at SuperKEKB.

Precision energy calibration at the Z and WW energies is achieved by the technique of resonant depolarisation, which was successfully used at VEPP-2M, VEPP-4M, CESR, DORIS, and LEP [19]. Supporting this effort, an FCC-EIC collaboration has added spin tracking [20] to the modern CERN accelerator simulation framework Xsuite [21].

The RF reverse phase operation, used only on the Z pole, was demonstrated with high beam current at the former KEKB [22], and it has also been adopted for the US Electron Ion Collider (EIC) [23].

Table 1: Parameters of FCC-ee [9].

Running Mode	**Z**	**WW**	**ZH**	**$t\bar{t}$**
Beam energy (GeV)	45.6	80	120	182.5
Bunches/beam	11200	1780	440	60
Beam current [mA]	1283	135	26.8	5.1
Luminosity/IP [10^{34} cm^{-2} s^{-1}]	144	20	7.5	1.45
Energy loss / turn [GeV]	0.039	0.369	1.86	9.94
Synchrotron Radiation Power [MW]	100	100	100	100
RF Voltage 400 / 800 MHz [GV]	0.08 / 0	1.0 / 0	2.1 / 0	2.1 / 9.2
Rms bunch length (SR) [mm]	5.53	3.46	3.26	1.91
Rms bunch length (+BS) [mm]	15.7	5.28	5.59	2.33
Rms relative momentum spread (SR) [%]	0.039	0,069	0.102	0.152
Rms relative momentum spread (+BS) [%]	0.115	0.105	0.176	0.186
Rms horizontal emittance ε_x [nm]	0.71	2.16	0.66	1.51
Rms vertical emittance ε_y [pm]	2.3	2.0	1.0	1.4
Hor. / vert. IP beta $\beta^*_{x\ /\ y}$ [mm]	110 / 0.7	220 / 1.0	240 / 1.0	900 / 1.4
Total beam lifetime [min.]	21	13	9	10
Total int. annual luminosity [ab^{-1}/yr]	68†	9.6	3.6	0.67‡

† The integrated luminosity in the first two years of Z running is assumed to be half this value to account for the machine commissioning and beam tuning; for WW and ZH running no additional commissioning time is allocated.
‡ The integrated luminosity in the first year of $t\bar{t}$ running, at the slightly lower beam energy of 170 GeV to 175 GeV, is assumed to be about 65% of this value to account for the machine commissioning and beam tuning.

TECHNOLOGY

The underlying basic technology for constructing a collider like FCC-ee is available at least since half a century [24]. However, there has been a great advance in energy efficiency since the LEP era (Fig. 3). Ongoing and future R&D aims at further increasing FCC-ee energy and operational efficiency, and at cost minimisation.

The FCC-ee injector complex includes two separate linacs accelerating electrons and positrons up to a beam energy of 2.86 GeV, a damping ring (DR), and a high-energy linac, which increases the beam energy from 2.86 GeV up to 20 GeV. With the exception of the 2 GHz positron capture linac, all linacs are operated at S-band frequency (2.8 or 3 GHz) with a mechanical structure concept based on the PSI SwissFEL. Synergies also exist with the 750 MeV S-band injector linac with a repetition rate of 30 Hz considered for the EIC [25]. The maximum repetition rate for the FCC-ee injector linacs is 100 Hz with at most 4 bunches per pulse. Positrons are required at a rate that, within a factor of two, equals the rate obtained at the SLAC SLC and SuperKEKB. Accordingly, the FCC-ee positron source is based on a conventional scheme using 2.86 GeV electrons from the electron linac impinging on a tungsten target, with a novel non-insulated High-Temperature Superconductor solenoid at design peak field of 12.5 T, serving as an adiabatic matching device. A scalable positron production and capture experiment, "P^3," is under construction at the PSI SwissFEL (Fig. 4). First experimental results on the positron yield are expected in 2026. The FCC-ee injector linacs and damping ring can be located on the CERN Prévessin site, and connected by a 5.6 km long transfer line to the collider tunnel. This working hypothesis is illustrated in Fig. 5.

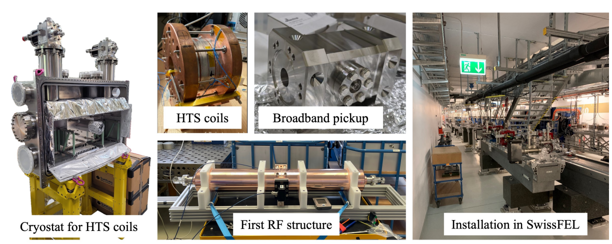

Figure 4: FCC-ee P^3 component production and installation in the SwissFEL.

The collider RF system for the first three sub-stages (Z, WW and ZH) is based on 2-cell 400 MHz superconducting Nb/Cu cavities operated at 4.5 K. The RF system for the booster and the additional collider RF cavities for the $t\bar{t}$ sub-stage are based on 6-cell bulk Nb cavities at 2 K. Parameters are summarized in Table 2. A prototype 5-cell 800 MHz bulk Nb cavity for the FCC-ee was built at JLab [26]. Two types of cryomodules are planned to accommodate the 400 MHz and 800 MHz cavity strings, covering the four operating modes of FCC-ee. The first type is designed for operation at 4.5 K and will house four 2-cell 400 MHz cavities, with a total length of 11.24 m; see Fig. 6. For the 6-cell 800 MHz cavities, the cryomodule will be designed to operate at 2 K, with an expected total length of 10.25 m. The 800 MHz cryomodule conceptual design is based on the PIP-II HB650 cryomodule, with the strongback support for the cavity string, and has been developed in collaboration with the Fermi National Accelerator Laboratory in the US.

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Table 2: Main RF Parameters of the FCC-ee collider [9].

Parameter	Z	WW	ZH	$t\bar{t}$	
Common RF system for two beams	no	no	yes	yes	
Reverse Phase Operation	yes	no	no	no	
Total RF voltage [MV]	89	1049	2098	2098	9202
Beam current [mA]	1283	135	53.6	10	
RF frequency [MHz]		400.79		400.79	801.58
Operating temperature [K]		4.5		4.5	2
Number of cells per cavity		2		2	6
Quality factor Q_0		2.7×10^9		2.7×10^9	3×10^{10}
Cavity voltage [MV]		7.95		7.95	22.5
Accelerating gradient E_{acc} [MV/m]		10.6		10.6	20.1
RF power per cavity [kW]		380		78	195
Coupling factor Q_L		9.2×10^5		4.5×10^6	4.1×10^6
Number of cryomodules		66		66	102
Number of cavities		264		264	408

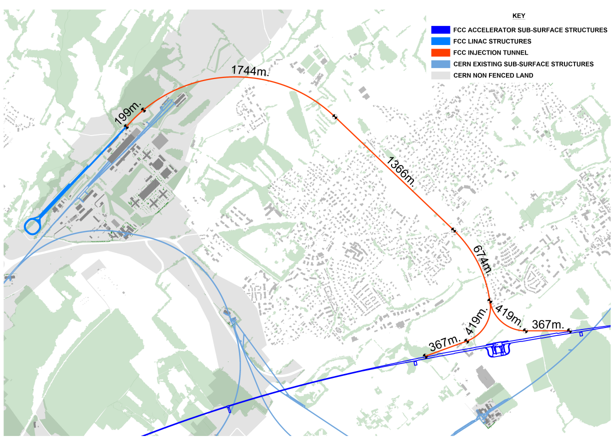

Figure 5: Plan view of FCC-ee injector complex on the CERN Prévessin site and the associated transfer lines to the collider tunnel, which also houses the booster [9].

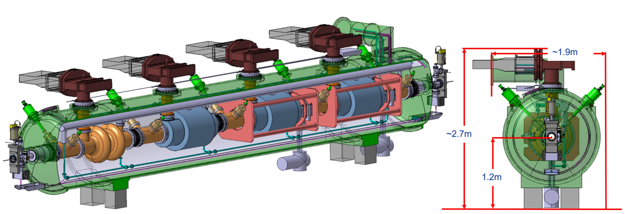

Figure 6: View of the 400 MHz cryomodule [9, 16].

The 400 MHz cavities and cryomodules are all installed in their final location from the start of operation, which represents two times 33 cryomodules in one of the collider technical straights. This approach avoids a staged installation of the cryogenics systems and later interventions in the tunnel for installing additional cryomodules. With the scheme of reverse phase operation for the 400 MHz RF, the transition between the Z and WW modes of operation involves only a reconfiguration of the RF system without any hardware intervention; the beamlines and beam paths stay the same, with each beam traversing half of the collider-RF cryomodules. The transition to the ZH operating point requires that both beams pass through the entire set of 66 cryomodules. The switch between the beam paths for Z and WW operation and for ZH operation, respectively, is achieved by remotely changing a combination of magnet strengths and electrostatic fields, again with no hardware intervention.

In simulations at CERN, a tristron was studied and optimised, as a candidate FCC-ee RF power source [27]. The final multi-beam (10 beams) tristron design at 400 MHz promises an excellent performance in the RF power range from 300 kW to 600 kW with simulated efficiency exceeding 90%. A snapshot of particle dynamics in the tristron and simulated RF power/efficiency performance at different operating voltages are shown in Fig. 7. Compared to a two-stage multi-beam klystron, the tristron provides a much more compact and more energy-efficient solution.

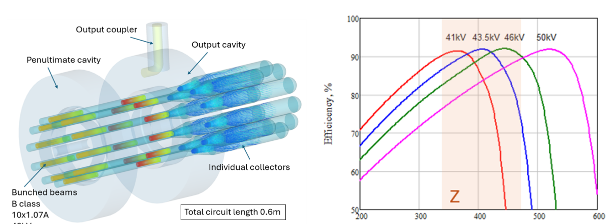

Figure 7: Left: Snapshot of particle dynamics in the proposed tristron power source for FCC-ee, simulated in 3D PIC CST [9, 16]. Right: Simulated RF power / efficiency performance at different operating voltages [9, 16].

The collider arc vacuum chamber is made of oxygen-free silver-bearing (OFS) copper and can be extruded up to 12 m. The chamber has two appendages, called winglets, in the horizontal plane, to accommodate short, localised synchrotron radiation absorbers (SRAs) and pumping slots. A sawtooth

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profile introduced on the inclined surface of the SRA reduces the primary photoelectrons inside the chamber proper. An innovative 'thin' NEG-coating [28] will be applied all along and throughout the vacuum chamber. This NEG-coating maintains its properties over 10 cycles of saturation and re-activation [29] for thicknesses down to 200 nm, compatible with impedance requirements. The booster chamber consists of a round seamless pipe in 1.5 mm thick OFE copper, with an inner diameter of 60 mm. A copper tube is spot welded on it for water cooling. No discrete photon absorber is planned in the booster in view of its low beam current and small duty factor. The booster chamber is neither coated nor baked.

The arcs cover about 77 km of the FCC-ee circumference. The regular FODO lattice of the collider ring features 2840 arc half-cells, with a length of about 25 m each, composed of a short straight section (SSS) followed by a series of dipole magnets. The SSS hosts a quadrupole and, depending on the position along the lattice, zero, one or two sextupole magnets. The total dipole length is adapted to occupy all the available space, maximising the dipole filling factor in the machine. The dipole and quadrupole magnets are designed as twin aperture units [30]; prototypes were built and measured.

A mock-up of an arc half-cell is being constructed. It will allow testing the integration of different simplified elements, assessing the access conditions, exploring alignment strategy and mechanical stability, etc. Subsequently, a continually evolving mock-up will enable equipment groups to install and, possibly, test their prototypes. The mock-up could, finally, house the full-size/weight functional elements. The scale will be 1:1, meaning that the 5.5 m diameter tunnel, and the half-cell length at high machine energy (30 m), are accurately reproduced. As shown in Fig. 8, the mock-up structure will be made of steel, featuring an arch every 3 metres, reinforced by transverse beams.

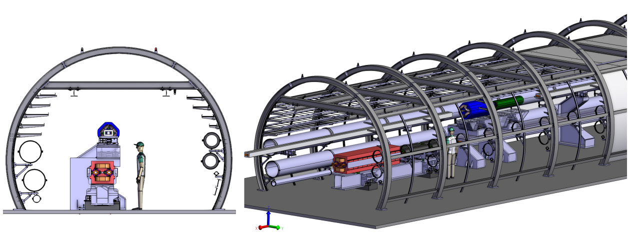

Figure 8: Schematic of the FCC-ee arc half-cell mock-up structure at CERN [9, 16].

SLAC and BNL are contributing to the development of the FCC-ee machine-detector interface [31]. The construction of a full scale mock-up of the interaction region (IR) is being assembled at INFN-Frascati in collaboration with INFN-Pisa, and CERN. It will be used to study the integration sequence of components, to help develop the IR alignment system, and to conduct a vibration analysis.

PATH TO CONSTRUCTION

At present, the FCC Collaboration comprises 161 institutes from 38 countries, including, in North America, 12 from the United States, 6 from Mexico, and 1 from Canada; see Fig. 9. A total of 45 U.S. institutes participate in FCC Physics, Experiments and Detector studies, many of which also signed Expressions of Interest for FCC detector R&D.

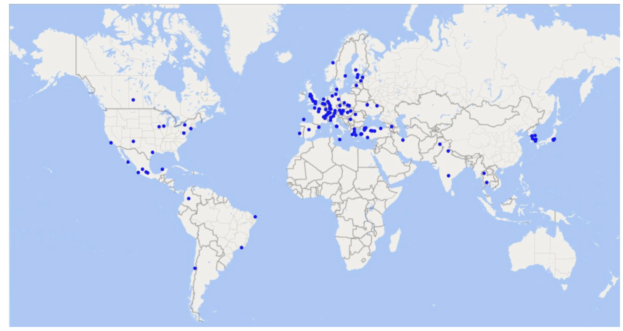

Figure 9: Status of the FCC global collaboration.

A project implementation scenario was developed and an analysis of the present territorial and environmental conditions indicates favorable prospects for construction. A socio-economic impact assessment integrating environmental aspects revealed a positive benefit-cost ratio. Dialogues with the public and host-state authorities have started.

Placement studies for the FCC are well advanced. CERN and Fermilab collaborated on design and 3D modeling of two specific surface sites [32]. The further FCC timeline is mainly determined by the preparation of the civil engineering—subsurface investigations, civil engineering design and tendering, and the project authorisation processes with the host states, all advancing in parallel. This will be followed by the civil construction and the subsequent installation of technical infrastructure and accelerator components. Key dates, including past work, are shown in Table 3. The ESPP Open Symposium 2025 revealed that the high-energy physics communities in the CERN member states along with those in the United States and Canada overwhelmingly support the integrated FCC-ee/hh programme [33].

Table 3: FCC-ee Timeline

Milestone / Phase	Years
Conceptual Design Study	2014 – 2018
Territorial implementation studies	2016 – 2025
Definition of placement scenario	2022
Earliest Project Approval	2027/28
Envir. eval. & author. processes	2026 – 2031
Technical Design Report ready	2032
Civil engineering	2033 – 2041
Techn. infrastr. installation	2039 – 2043
Accelerator installation	2041 – 2045
Hardware commissioning	2042 – mid 2046
Start beam operation	mid 2046 – 2047
Nominal beam operation	2048 – 2062

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