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Future Circular Collider Study

Lepton Collider Parameters

WBS PATH

1.4.1.2

ABSTRACT:

The goal of the FCC-ee Lepton Collider is to provide e^+e^- collisions in the beam energy range of 40 to 175 GeV. The main centre-of-mass operating points with large physics interest are 91 GeV (Z-pole), 160 GeV (W pair production threshold), 240 GeV (Higgs resonance) and 350 GeV (ttbar threshold). The expected machine circumference is around 100 km. The machine should accommodate up to four experiments operated simultaneously and deliver peak luminosities above 1×10^{34} $cm^{-2}s^{-1}$ per experiment at the ttbar threshold and higher luminosities at lower energies. This document summarizes the second version of FCC-ee baseline parameters.

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HISTORY OF CHANGES

REV. NO.	DATE	PAGES	DESCRIPTIONS OF THE CHANGES
0.0	2014-01-10	All	First FCC-TLEP baseline version from Jorg Wenninger and Frank Zimmermann. The parameters are based on those of the 6th TLEP Workshop, but with lower beam-beam parameters
0.1	2014-01-21	All	for the Z (~1/2) and W(~0.7) operating points.
0.2	2014-01-22	All	Reviewed by J. Wenninger
0.3	2014-01-26	n/a	QA check by J. Gutleber
0.4	2014-01-27	n/a	Document received by JWE with modifications to V0.0
0.5	2014-01-27	All	Merge by JGU of version V0.2 and additions to V0.0 QA checked by MBE, JWE, JGU before distribution
0.6	2014-02-01	All	Incorporated comments from approval. Improved the performance at the H and ttbar. Name changed from TLEP to FCC-ee.
1.0	2014-02-10	All	Reviewed by M. Benedikt and incorporation of comments for release of baseline version 1.0
1.1	2014-08-29	All	Corrected the beam sizes at the IP for the 80 GeV/W operation column (table 1). Values were not correct. Corrected the radiative bhabha cross-section and updated the luminosity lifetimes in table 1. Added an appendix section on the radiative Bhabha cross-section.
2.0	2014-09-05	All	QA check by JGU, set to RELEASED 2.0
2.1	2016-03-04	All	Second version of the parameters with crossing angle at IP of 30 mrad, 2 experiments, vertical beta* 2 mm.
3.0	2016-06-21	All	Adjustment of baseline drawing to applicable standard. JGU QA and set to RELEASED

TABLE OF CONTENTS

1. Introduction

1.1 Purpose

The purpose of this document is to define a parameter baseline for the lepton collider (FCC-ee) of the Future Circular Collider (FCC) study. This document presents the second version of the parameters, updated 2 years after the FCC study kickoff.

1.2 Scope

The goal of the Future Circular Collider lepton collider is to provide e^+e^- collisions in the beam energy range of 40 to 175 GeV [1]. The main centre-of-mass operating points with large physics interest are around 91 GeV (Z-pole), 160 GeV (W pair production threshold), 240 GeV (Higgs resonance) and 350 GeV (ttbar threshold). The machine would have a circumference of the order of 80 to 100 km, allowing to reach these four operating regions with acceptable synchrotron radiation power. The machine should be able to support up to four experiments operated simultaneously and deliver to each experiment a peak luminosity above $1\text{x}10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$ at the ttbar threshold and even much higher luminosities at lower energies.

1.3 Definitions, Acronyms and Abbreviations

SI units and formatting according to standard ISO 80000-1 on quantities and units are used throughout this document where applicable.

The four baseline operation energies are referred to a Z (91 GeV), W (160 GeV), H (240 GeV) and ttbar (350 GeV) operation points.

c.m.	Centre of Mass
FCC	Future Circular Collider
FODO	Focusing and defocusing quadrupole lenses in alternating order
BS	Beamstrahlung
IP	Interaction Point
FF	Final focus
LSS	Long straight section
LHC	Large Hadron Collider
RF	Radio Frequency
SR	Synchrotron Radiation
RDP	Resonant Depolarization (for energy calibration)
TBC	To Be Confirmed
TBD	To Be Defined

1.4 References

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1.5 Overview

Section 1 gives an overview, explains abbreviations and terms and lists references.

Section 2 introduces assumptions and constraints that impact the parameter set.

Section 3 contains the table of baseline parameters.

2. Collider Parameters

2.1 Baseline layout

The latest machine baseline assumes a layout with 12 arcs and 12 long straight sections (LSS) as shown in Figure 1. The arc and LSS lengths depend on their usage for FCC-hh (experiments, collimation etc), the total length of the machine is currently set to 100 km. A possible FCC-ee layout compatible with the FCC-hh layout [2] is presented in Figure 2. For a filling factor of 0.84 the bending radius is 11 km for a 100 km machine and the required bending field in the dipole magnets ranges from 130 to 540 G (13 to 54 mT).

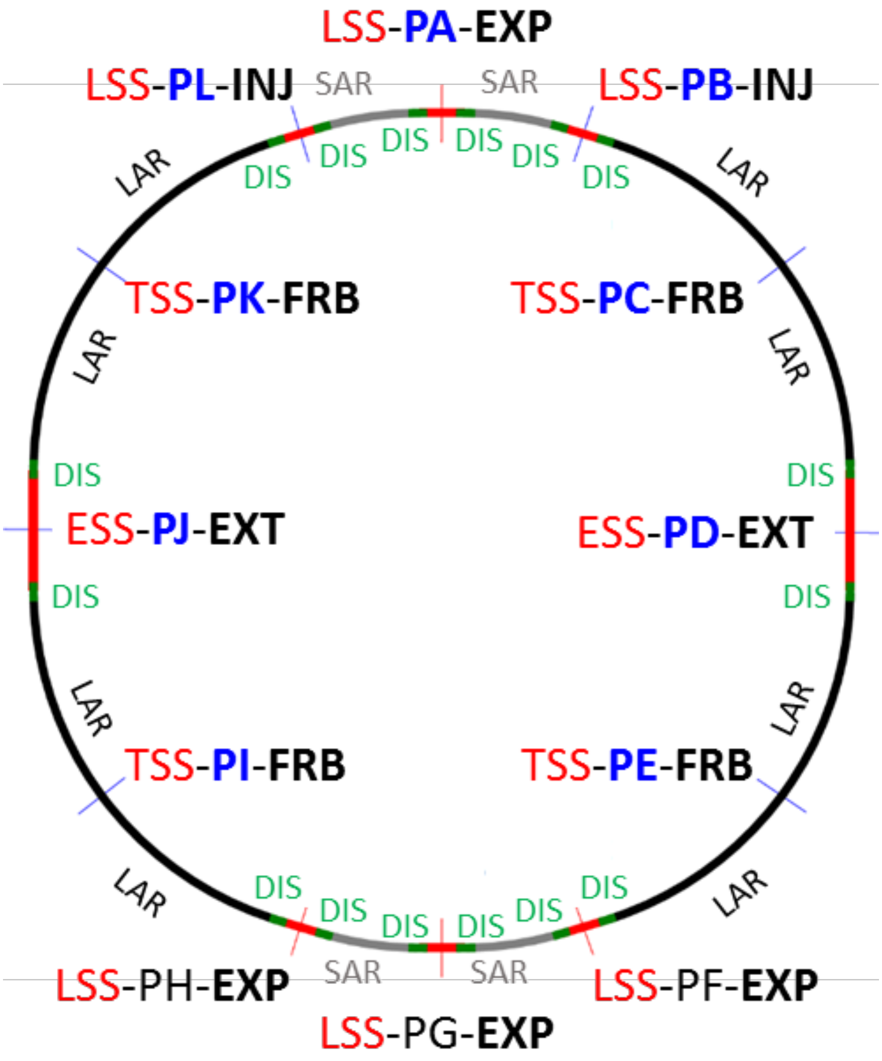

Figure 1: Layout of the FCC-hh hadron collider.

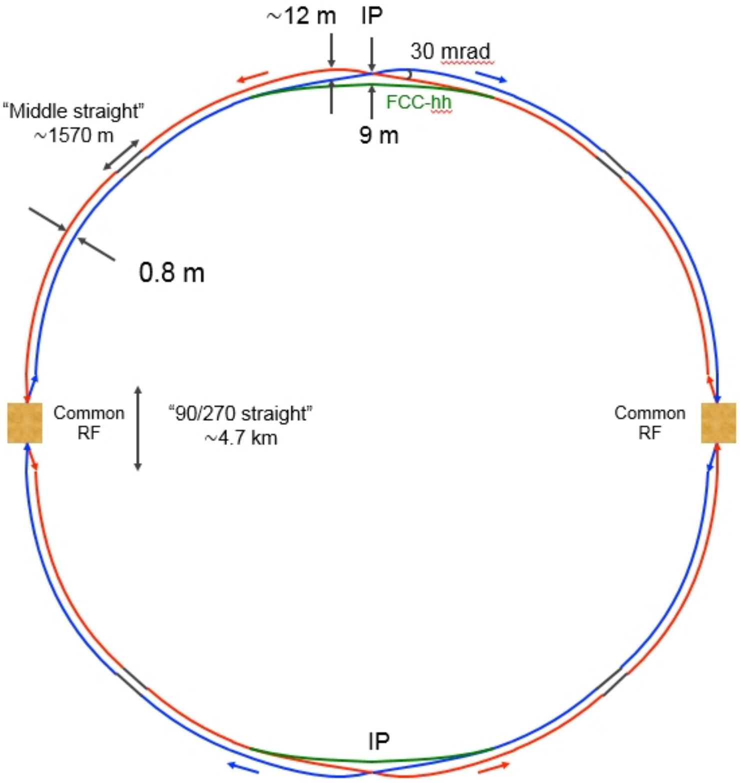

Figure 2: Possible layout of the FCC-ee with two experiments (labelled IP).

To accommodate more than 50'000 bunches for operation at the Z pole and many thousand bunches for operation at the W threshold, the two beams must circulate in separate vacuum chambers in the arc sections and in all the LSSs without experiments. This concept is similar to the LHC and to other modern high luminosity factories such as DAFNE, KEKB and PEPII. It is estimated that with a common vacuum chamber for both beams in the entire collider, as was the case for LEP, the number of bunches would be limited to a few hundred.

The straight sections have to accommodate up to four main experiments. The current baseline considers only two high luminosity experiments that are placed on opposite sides of the ring [2].

Due to the large energy loss per turn at 175 GeV (~4.5%) it is in principle favorable to distribute the RF system evenly over the ring to minimize radial orbit excursions due to the energy sawtooth. An alternative and possibly simpler and cheaper option involves shimming the dipole and quadrupole magnets to compensate for the energy offsets from the energy sawtooth. Such a tapering scheme would minimize the orbit excursions and the associated optics perturbations. This would relax the requirements on the RF system distribution over the ring which could be concentrated in two LSS. The optimization of the RF system layout is clearly an important item of the FCC-ee study.

The other LSSs will be used for injection, beam dump and collimation systems. The detailed layout will be optimized in conjunction with the FCC-hh.

Staging scenarios for the machine, concerning for example the RF system, will be evaluated during the study.

2.2 Beam parameters

2.2.1 Introduction

A wide parameter space exists for the beam parameters, which is constrained by different limitations. In the following we describe how the current baseline parameter sets were chosen and have evolved since the FCC kick-off meeting. Studies are ongoing to confirm their validity and to further optimize parameters.

The most important parameters for the experiments are luminosity (L), beam energy (E) and polarization (P).

2.2.2 Beam currents

The total beam current is defined by the acceptable synchrotron radiation power. At this stage the maximum SR power is set to 50 MW per beam for all energies. Since the energy loss per turn scales with E^4, the total beam current drops $\propto 1/E^4$. The beam current varies between 1.4 A at 45.5 GeV and 7 mA at 175 GeV. The SR power budget does not take into account losses outside of the arcs, for example losses in dipole magnets or other elements required to bring the two beams together in the LSSs. Such losses will be taken into account when work on the machine layout will be sufficiently advanced. They are expected to affect the total beam current at the level of one percent.

2.2.3 Luminosity and bunch parameters

The luminosity can be expressed as a function of the beam current I, the vertical beam-beam parameter ξ_y and the vertical betatron-function at the collision point β_y^* as

$$L = \xi_y \frac{I}{e}\frac{\gamma}{\beta_y^*}\frac{1}{r_e}H$$

Here r_e is the classical electron radius and e its charge. I is the total beam current and γ the ratio of energy over rest mass of the electron. H is the hourglass factor. For flat beams crossing with a horizontal angle θ at the IP, the beam-beam parameters may be expressed as a function of the beam sizes at the IP σ_x* and σ_y* and the bunch population N [7] as

$$\xi_x = \frac{r_e}{2\pi\gamma}\frac{N\beta_x^*}{\sigma_{xs}^*(\sigma_{xs}^* + \sigma_y^*)} \approx \frac{r_e}{2\pi\gamma}\frac{N\beta_x^*}{\sigma_x^{*2}(1+\phi^2)} = \frac{r_e}{2\pi\gamma}\frac{N}{\varepsilon_x(1+\phi^2)}$$

and

$$\xi_y = \frac{r_e}{2\pi\gamma}\frac{N\beta_y^*}{\sigma_y^*(\sigma_{xs}^* + \sigma_y^*)} \approx \frac{r_e}{2\pi\gamma}\frac{N\beta_y^*}{\sigma_y^*\sigma_x^*(1+\phi^2)^{1/2}}$$

where

$$\sigma_{xs}^{*2} = \sigma_x^{*2}(1+\phi^2).$$

ϕ is the Piwinski angle

$$\phi = \frac{\sigma_s}{\sigma_x^*}\tan(\theta/2),$$

and σ_s is the r.m.s. bunch length. The form factor F (≤1) in the expression of ξ_y,

$$F = \frac{1}{\sqrt{1+\phi^2}},$$

corresponds to the geometric luminosity reduction due to the crossing angle between the two beams. For the current parameter set the horizontal crossing angle θ is 30 mrad and F varies between 0.2 (Z) and 0.8 (ttbar) due to the increasing horizontal beam size with energy.

The hourglass factor H (≤1) gives the luminosity reduction due to the change of the vertical β^* over the interaction region L_i. The length L_i of the interaction region between the two beams is

$$L_i = F\sigma_s$$

For $\phi = 0$, i.e. for head-on collisions, L_i corresponds to the bunch length. H becomes significantly smaller than 1 when L_i exceeds β^*. For the current parameter set $H \approx 0.9\text{-}1$ because the interaction region is always smaller than the vertical β^*.

For a given energy the horizontal beam-beam parameter depends only on bunch population N, emittance and ϕ. ξ_x can thus be controlled through the emittance with the lattice phase advance, with the damping partition numbers (e.g. LEP2) or with wigglers (e.g. LEP1). Due to the large synchrotron radiation losses induced by wigglers, the last option has probably to be discarded for FCC-ee, respectively cam only be used for a limited range of emittance change. The horizontal beam-beam tune shift may also be controlled through ϕ because ξ_x scales with $(1+\phi^2)^{-1}$ while luminosity and vertical beam-beam tune shift scale only with $(1+\phi^2)^{-1/2}$.

For the initial baseline parameters an upper limit for the total beam-beam tune shift ξ_y was scaled from the observations made at LEP [4]. Scaled to FCC-ee the maximum parameter ranged between 0.027 at 45.5 GeV and 0.137 at 175 GeV. More recent beam-beam simulations for FCC-ee including the horizontal crossing angle and crab-waist schemes [6] result in significantly higher values for the beam-beam limit. Those new limits were taken account into the definition of the new baseline parameters [2].

The fractional phase advance between any pair of IPs should be close to the half integer, around 0.54-0.6 [8]. For 2 IPs the fractional tune is therefore in the range 0.08 to 0.2. A larger fraction tune is favored for the vertical plane to ease the correction of the vertical dispersion.

At very high luminosity photon radiation at the IP in the field of the counter rotating bunch (‘Beamstrahlung’, BS) becomes a limitation to the performance of the colliders [9] [10]. The strength of BS may be expressed by the average bending radius ρ_{BS} of the particles in the field of the opposing beam [10]:

$$\frac{1}{\rho_{BS}} \approx \frac{N r_e}{\gamma \sigma_x^* \sigma_s} \sqrt{2}$$

σ_x* is the horizontal beam size at the IP and σ_s is the bunch length. ρ_{BS} can be lowered by increasing the bunch length and using flat beams at the IP ($\sigma_x^* >> \sigma_y^*$). The BS lifetime τ_{BS} can be expressed as

$$\tau_{BS} \propto \frac{\rho_{BS}^{3/2} \eta^{1/2}}{\sigma_s} \exp(A \eta \rho_{BS})$$

A is a constant and η is the energy acceptance of the ring (RF and lattice). A large acceptance of ~2% is required at FCC-ee for the H and ttbar operation points. At those operation points the BS lifetime can easily drop to a few minutes only, and a careful optimization of the beam parameters and optics is required to ensure a sufficient lifetime margin. The process requires tracking studies since the equilibrium bunch lengths and the beam sizes are affected by the beam-beam interaction and by BS; a self-consistent calculation is required for reliable predictions. For the Z and W operating points a momentum acceptance of 1% is sufficient.

The luminosity lifetime is limited by the burn-off of the beam which is dominated for FCC-ee by radiative Bhabha scattering. At LEP the effective total cross-section for radiative Bhabha scattering was observed to be approximately independent of energy, the absence of the expected energy dependence is due to field screening inside the bunch. A cross-section of $\sigma_{ee} \approx 0.21$ (b) was measured at LEP [2], in good agreement with simulations with the program BBREM [11][2]. The program BBBREM was used to estimate the cross-section for FCC-ee for a momentum acceptance of 2%. The energy dependence was found to be weak, in agreement with the LEP observations. A central value of $\sigma_{ee} = 0.15$ (b) was chosen for FCC-ee. A more accurate value for the cross-section will be evaluated in the future for the final energy acceptance. The beam lifetime due to radiative Bhabha scattering is

$$\tau_L = \frac{I}{e L n_{IP} \sigma_{ee}}$$

The lifetime depends directly on the number of IPs n_{IP}. At the H and ttbar operation points τ_L is around 60 minutes with two IPs.

Other limitations for beam parameters need to be studied, e.g. collective instabilities and electron cloud effects. These may restrict the range of available choices. At the Z operation point the bunch spacing is 2.5 ns which may trigger important electron could activity.

2.3 Accelerator lattice

The arc lattice design work currently considers a FODO cell with a length of 50 m optimized for an emittance around 1 nm at 175 GeV. The dipole magnet length is 11m, and should not be increased to avoid impact of the synchrotron radiation fan within the magnet itself which could complicate the layout of the vacuum system and the integration of photon stops. For a constant lattice the natural scaling of the emittance leads to an important reduction at a lower energy due to the scaling

$$\varepsilon_x \propto \frac{E^2}{J_x Q^3}$$

Q is the horizontal tune (~ 400) and J_x is the horizontal damping partition number, $J_x=1$ for the current FCC-ee parameter set. The momentum compaction factor α_c ~ 7E-6 for the current baseline lattice with 90º phase advance in the horizontal plane.

For the current baseline the same lattice is used at all energies, which leads to a reduction of the emittance at the lower energies. For the Z parameter variant with lower β^*, the emittance should be increased to control BS effects, see Table 1.

The first baseline parameter set considered to adapt the phase advance by a change of cell length to maintain a sufficiently large emittance (control of the horizontal beam-beam parameter) at lower energy. With the crossing angle of 30 mrad and crab waist schemes this is not necessary and the same lattice can be used for all energies. The possibility of changing the phase advance is nevertheless still an option to gain some flexibility to control beam-beam effects.

2.4 Interaction region

A lower limit for the vertical beta-function arises from the final focus, the distance between IP and first quadrupole (L*) and the chromatic corrections. A vertical β^* of 1 mm was set as initial baseline parameter. So far best momentum (2%) and dynamic apertures were achieved for β^* of 2 mm with two experiments. For this reason a β^* of 2 mm has been adopted for this baseline, but the long term target still aims for a smaller value in particular at lower energies. Optics versions with a vertical β^* of 1 mm but somewhat lower DA and momentum acceptance are already available. A smaller vertical β^* can be used to increase the performance at the Z and W, beam-beam simulations currently indicate however that a reduction of the vertical β^* does not yield significant luminosity gains at the higher energies. The horizontal β^* on the other hand must be kept large (around 0.5-1 m) since flat beams with large σ_x^* improve the BS lifetime.

The very large chromaticity from the final focus is corrected locally with sextupoles. Crab sextupoles are installed in addition to provide a full crab waist scheme.

To reduce the synchrotron radiation load due to dipoles near the IR an asymmetric layout of the FF has been proposed [2], see Figure 2. This reduces the critical energy of photons below 100 keV even at the highest energy. A few asymmetric IR layouts are now available with different tunnel geometries and photon spectra [12].

2.5 RF parameters

For the present baseline a 400 MHz RF system is considered as a default to maintain sufficiently short bunch lengths and remain compatible with the standard CERN RF systems. The total RF voltage at the ttbar threshold is 10 GV. It is currently assumed that the effective length of the RF system will be 600 m for a maximum gradient of 20 MV/m for a given beam. For the 400 MHz RF system the number of RF buckets is h = 133’426. For the Z parameter set with ~90’000 bunches, essentially every bucket must be filled.

An important optimization concerns the total size of the RF system. Due to lower RF voltage requirements, less than half of the full RF cavity system is needed for the Z, W and H operation points. In combination with the very high beam currents it may be possible to split the full RF system in two parts that are dedicated to a single beam (300 m per beam) at those energies. At the highest energy (H and ttbar) the same RF system may be used for both beams as was the case for LEP, requiring however a change of the machine layout for ttbar operation. Such considerations require a careful optimization of the ring layout.

2.6 Injector chain and booster ring

The short lifetimes from radiative Bhabha scattering and from BS, potentially as low as 10 minutes or less depending on the parameter sets, require continuous top-up injection. The FCC-ee collider will therefore be operated at constant energy and must be continuously filled by a cycling booster ring. The booster is installed in the FCC tunnel and has its own RF system, with same length and total voltage as for the FCC-ee collider. The booster ring will be used alternatively for e^+ and e^- beams. The currents in the booster will be much lower than in the collider ring, at the level of few percent of the full current of the Z point, which corresponds to a few tens of mA. The required RF power is therefore much lower (more than a factor 10). The booster will be cycling between its injection energy of 10 - 40 GeV and the operating energy of FCC-ee. The lower limit for injection energy may be given by magnetic field, aperture and impedance considerations. The higher limit on the energy will be defined by the cost and complexity of the injector chain. The maximum repetition rate is currently estimated to be around 0.1 Hz. The required flux of e^+ and of e^- is currently estimated to be 2×10^{12} particles per second for each species. This number does not take into account transfer efficiencies between the different elements of the accelerator chain.

2.7 Polarization

Beam polarization is an important parameter for operation at the Z and W.

Resonant depolarization (RDP) of a transversely polarized beam provides an exceptionally accurate measurement of the beam energy, to the level of 0.1 MeV or better. Such accuracy is required to reduce by an order of magnitude the uncertainties on the Z boson mass and width [1]. Such an improvement of the accuracy requires continuous monitoring of the beam energy with for example polarized non-colliding bunches. With the very small momentum compaction factor of FCC-ee (at level of few 1E-5), the range of energy variations over a year is expected to be larger than 100 MeV (earth tides, geological movements etc). The interpolation of the average beam energy as determined by RDP to the IPs requires an excellent understanding of all sources of energy loss and energy gain (for example RF cavity voltages and phases). Local energy measurements may have to be installed to set constraints on the energy along the ring, first concepts based on Compton scattering have been proposed [2].

Electron (and positron) beams polarize spontaneously in storage rings due to the emission of synchrotron radiation up to an equilibrium level of 92.4%. The build-up time of polarization τ_P scales like

$$\tau_P \propto \frac{\rho^3}{E^5}$$

Compared to LEP1, τ_P is increased by a factor ~4^3 to around 200 hours which is excessively long. The rise time may be lowered to ~12 hours using wigglers at the price of a lower beam current to compensate the large (ten's of MW) power loss from the wigglers [5]. Such a rise time may be acceptable for energy calibration that only requires a few percent of polarization. Besides the issue of power, the use of wigglers is also limited by the induced energy spread. The LEP observations [3] indicate that the maximum tolerable energy spread is ~70 MeV (compared to the 440 MeV spacing of the integer spin resonances). For such a limit spontaneous polarization should be observable without wigglers at the W operation point of FCC-ee with τ_p ~10 hours, as compared to LEP, where the larger energy spread prevented build-up of polarization at the W threshold.

Longitudinal polarization at the IP can be used for precise Left-Right asymmetry measurements at the Z pole. Such an option becomes interesting for polarization levels of 30% or more. Spin rotators would have to be installed around each IP where data taking with longitudinal polarization is foreseen.

Reaching at the same time a high level of polarization and a reasonable polarization time is a considerable challenge, requiring cancellation of depolarizing effects at a level of perfection that is much better than achieved in LEP. Various ideas will be investigated, such as Siberian snakes in the storage ring itself, or injection of a polarized beam from the booster or from a dedicated polarizing damping ring in combination with Siberian snakes. Such options must be studied in detail [2].

3. Parameter Overview

The baseline parameters of FCC-ee are presented in the following Table 1. The previous baseline parameter table in shown in Appendix 4.1 (Table 2).

The energy acceptance η of FCC-ee is assumed to be 2% at all energies, but it should be noted that such a large acceptance is not required at the Z and W operation points.

The emittance ratio is set to 0.1% or larger, with the constraint that the absolute vertical emittance should not be smaller than ~1 pm; this is a challenging target for such a large machine, requiring excellent vertical dispersion and coupling control. It is assumed that the same lattice is used at all energy points, which is the reason for the strong reduction of the emittance with energy.

The baseline vertical betatron function at the IP has been increased from 1 mm to 2 mm to match the current state of the optics development. At the higher energies (H,t) there is little or no gain from lowering the vertical β*. At the Z (and possibly W) an increase of the luminosity may be obtained from a reduction of β* in both planes. A possible configuration with vertical β* of 1 mm for Z operation is presented in the parameter table.

The number of IPs has been reduced from 4 to 2, which improves by a factor 2 the luminosity lifetimes.

A crossing angle of 30 mrad at the IP is now the baseline configuration, while the initial parameter set assumed head-on collisions which were in fact inconsistent with the assumed number of bunches, in particular at the Z pole.

With respect to the previous baseline the RF frequency has been halved to 400 MHz. As a consequence the bunch lengths are longer, but with the crossing angle of 30 mrad the beam overlap region (interaction region) is always smaller than 1.7 mm which matches the value of β_y* (hourglass effect).

Both energy spread and bunch length are quoted for a non-colliding beam, where the values are given by the equilibrium spread from synchrotron radiation in the arc, and for colliding beams which includes photon emission at the IP (BS). As can be seen in the table there is a significant blow-up of the beams due to radiation at the IP.

The new beam-beam parameter values are consistent with tracking results [2][5].

Table 1: FCC-ee baseline parameters.

	Z	Z	W	H	tt
Circumference [km]	100				
Bending radius [km]	11				
Beam energy [GeV]	45.6		80	120	175
Beam current [mA]	1450		152	30	6.6
Bunches / beam	30180	91500	5260	780	81
Bunch spacing [ns]	7.5	2.5	50	400	4000
Bunch population [10^{11}]	1.0	0.33	0.6	0.8	1.7
Horizontal emittance ε [nm]	0.2	0.09	0.26	0.61	1.3
Vertical emittance ε [pm]	1	1	1	1.2	2.5
Momentum comp. [10^{-5}]	0.7	0.7	0.7	0.7	0.7
Betatron function at IP					
- Horizontal β^* [m]	0.5	1	1	1	1
- Vertical β^* [mm]	1	2	2	2	2
Horizontal beam size at IP σ^* [μm]	10	9.5	16	25	36
Vertical beam size at IP σ^* [nm]	32	45	45	49	70
Crossing angle at IP [mrad]	30				
Energy spread [%]					
- Synchrotron radiation	0.04	0.04	0.07	0.10	0.14
- Total (including BS)	0.22	0.09	0.10	0.12	0.17
Bunch length [mm]					
- Synchrotron radiation	1.2	1.6	2.0	2.0	2.1
- Total	6.7	3.8	3.1	2.4	2.5
Energy loss / turn [GeV]	0.03		0.33	1.67	7.55
SR power / beam [MW]	50				
Total RF voltage [GV]	0.4	0.2	0.8	3	10
RF frequency [MHz]	400				
Longitudinal damping time [turns]	1320		243	72	23
Energy acceptance RF [%]	7.2	4.7	5.5	7.0	6.7
Synchrotron tune Q_s	0.036	0.025	0.037	0.056	0.075
Polarization time τ_p [min]	11200		672	89	13
Interaction region length L_i [mm]	0.66	0.62	1.02	1.35	1.74
Hourglass factor $H(L_i)$	0.92	0.98	0.95	0.92	0.88
Luminosity/IP for 2IPs [10^{34} cm^{-2}s^{-1}]	207	90	19.1	5.1	1.3
Beam-beam parameter					
- Horizontal	0.025	0.05	0.07	0.08	0.08
- Vertical	0.16	0.13	0.16	0.14	0.12
Luminosity lifetime [min]	94	185	90	67	57
Beamstrahlung critical	No/Yes	No	No	No	Yes

4. Appendix

4.1 Previous parameter table

The first version of the parameter table was defined for the FCC kickoff meeting that took place February 2014 in Geneva. The table is shown below as reference.

Table 2: Parameter table defined for the FCC kickoff meeting in 2014.

	LEP1	**LEP2**	**Z**	**W**	**H**	**tt**
Circumference [km]	26.7		100			
Bending radius [km]	3.1		11			
Beam energy [GeV]	45.4	104	45.5	80	120	175
Beam current [mA]	2.6	3.04	1450	152	30	6.6
Bunches / beam	12	4	16700	4490	1360	98
Bunch population [10^{11}]	1.8	4.2	1.8	0.7	0.46	1.4
Transverse emittance ε						
- Horizontal [nm]	20	22	29.2	3.3	0.94	2
- Vertical [pm]	400	250	60	7	1.9	2
Momentum comp. [10^{-5}]	18.6	14	18	2	0.5	0.5
Betatron function at IP β^*						
- Horizontal [m]	2	1.2	0.5	0.5	0.5	1
- Vertical [mm]	50	50	1	1	1	1
Beam size at IP σ^* [μm]						
- Horizontal	224	182	121	41	22	45
- Vertical	4.5	3.2	0.25	0.084	0.044	0.045
Energy spread [%]						
- Synchrotron radiation	0.07	0.16	0.04	0.07	0.10	0.14
- Total (including BS)	0.07	0.16	0.06	0.09	0.14	0.19
Bunch length [mm]						
- Synchrotron radiation	8.6	11.5	1.64	1.01	0.81	1.16
- Total	8.6	11.5	2.56	1.49	1.17	1.49
Energy loss / turn [GeV]	0.12(1)	3.34	0.03	0.33	1.67	7.55
SR power / beam [MW]	0.3(1)	11	50			
Total RF voltage [GV]	0.24	3.5	2.5	4	5.5	11
RF frequency [MHz]	352		800			
Longitudinal damping time τ_E [turns]	371	31	1320	243	72	23
Energy acceptance RF [%]	1.7	0.8	2.7	7.2	11.2	7.1
Synchrotron tune Q_s	0.065	0.083	0.65	0.21	0.096	0.10
Polarization time τ_p [min]	252	4	11200	672	89	13
Hourglass factor H	1	1	0.64	0.77	0.83	0.78
Luminosity/IP [10^{34} cm^{-2}s^{-1}]	0.002	0.012	28.0	12.0	6.0	1.8
Beam-beam parameter						
- Horizontal	0.044	0.040	0.031	0.060	0.093	0.092
- Vertical	0.044	0.060	0.030	0.059	0.093	0.092
Luminosity lifetime [min](2)	1750	434	298	73	29	21
Beamstrahlung critical	No		No	No	Yes	Yes

(1) Does not take into account the contribution of damping and emittance wigglers.

(2) The luminosity lifetime corresponds to 4 IPs.