A Baseline for the FCC-he

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Abstract

Initial considerations are presented on the FCC-he, the electron-hadron collider configuration within the Future Circular Collider study. This note considers arguments for the choice of the electron beam energy based on physics, *ep* scattering kinematics and cost. The default configuration for the electron accelerator, as for the LHeC, is chosen to be a multi-turn energy recovery linac external to the proton beam tunnel. The main accelerator parameters of the FCC-he are discussed, assuming the concurrent operation of *ep* with the 100 TeV cms energy *pp* collider. These are compared with the LHeC design concept, for increased performance as for a Higgs facility using the HL-LHC, and also the high energy HE-LHC *ep* collider configuration. Initial estimates are also provided for the luminosity performance of electron-ion colliders for the 60 GeV electron ERL when combined with the LHC, the HE-LHC and the FCC ion beams.

1 Introduction

Since the discovery of quarks in electron-proton scattering [1, 2], using the 2 mile electron linac at Stanford in 1968, deep inelastic scattering (DIS) has been established as the ideal means to explore the substructure of matter. The Stanford SLAC-MIT experiment was followed by a number of charged lepton and neutrino fixed target DIS experiments. Currently, the DIS energy frontier is held by HERA at DESY, which was the first *ep* collider ever built. Proposed in 1984, it operated between 1992 and 2007 with colliding electron and proton beams of energy $E_e = 27.5\,\mathrm{GeV}$ and $E_p = 920\,\mathrm{GeV}$, resp. The cms. energy was $\sqrt{s} = 2\sqrt{E_e E_p} = 319\,\mathrm{GeV}$, and the luminosity reached up to $4 \cdot 10^{31}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. The total integrated *ep* scattering luminosity was $0.5\,\mathrm{fb}^{-1}$ collected by H1 and by ZEUS in 15 years. HERA opened various new avenues of research with many instrumental and physics innovations [3]. Its measurements on proton structure [4] are the base for most of the current LHC data analyses with ATLAS and CMS. It was not given the time to study electron-deuteron nor electron-ion (eA) collisions.

The unique, intense hadron beams of the HL-LHC, and conceptually the FCC, enable a next large step for DIS physics through building a new, higher energy electron beam. This *ep* accelerator and detector configuration would be the cleanest microscope for substructure of matter which nowadays may be built. The “Large Hadron Electron Collider (LHeC)” has been designed for synchronous operation with the LHC. Its physics, a detector design and two machine options with their infrastructure have been studied in a series of workshops supported by CERN, ECFA and NuPECC, and they are described in detail in a Conceptual Design Report (CDR) which was published in 2012 [5]. The default LHeC configuration uses a 60 GeV energy electron beam derived from a racetrack, three-turn, intense energy-recovery linac (ERL) achieving a cms energy of $\sqrt{s} = 1.3\,\mathrm{TeV}$. To enable precision Higgs physics [6] and support a novel DIS programme, recently described in [7], the LHeC is currently developed further with the goal to achieve a luminosity of $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, that is ten times higher than considered in the CDR and based on the HL-LHC parameters [8]. Its main principle, a high current, multi-turn ERL is intended to be investigated with a lower energy test and development facility called PERLE [9].

This note focuses on a further future step in the enlargement of the *ep* collision energy which may be provided by the 50 TeV proton beam of the FCC-hh. Arguments are presented below for choosing the ERL electron beam of the LHeC as the baseline for also the FCC-he. This novel electron-proton collider would enable DIS physics at $\sqrt{s} = 3.5\,\text{TeV}$ with a luminosity of also the order of $10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$ in synchronous *ep* and *pp* operation. The kinematics of past and projected DIS experiments is illustrated in Fig. 1. The physics programme of the FCC-he, recently presented at the 2016 FCC workshop at Rome as well as the FCC physics week in January 2017, is extremely rich as, for example, it reaches values as small as 10^{-7} of Bjorken x in DIS scattering and enables clean Higgs physics with a 1 pb $ep \to \nu H X$ production cross section, besides offering a unique discovery potential in QCD and beyond the Standard Model.

This note describes in Sect. 2 the electron beam configuration, its footprint and energy choice. Section 3 presents an initial consideration of the baseline parameters for the FCC-he. This assumes that *ep* and *pp* operate synchronously while a special study may still be undertaken to investigate prospects of achieving luminosities $O(10^{35})$ in dedicated *ep* operation. Concluding, a summary of the basic collider parameters is presented for the LHeC, in its original and high luminosity configuration, for the HE-LHC based *ep* collider and the FCC-he. The LHeC and the FCC-he include options for high energy electron-ion (eA) scattering the parameters of which are listed in Sect. 4. A brief summary of this study is provided in Sect. 5.

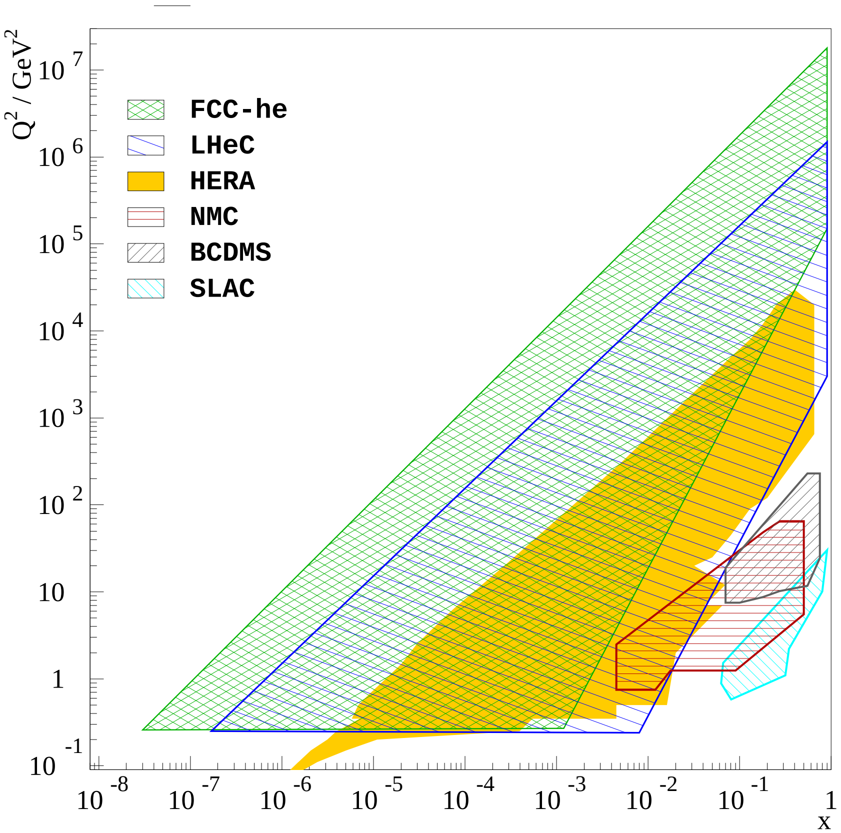

Figure 1: Kinematic plane of the negative 4-momentum transfer squared, Q^2, and the parton's momentum fraction, Bjorken-x, for fixed target experiments at SLAC and CERN, HERA, the LHeC and the FCC-he. In the US and China there exist proposals for new *ep* colliders with energies much lower than HERA but large luminosity, and also proton beam polarisation which is excluded at the LHC or FCC. In China there also are plans for *ep* colliders which are similar in energy to the FCC-eh.

2 Electron Beam

2.1 Footprint

In the LHeC default configuration [5] two super-conducting linacs are used to generate a polarised electron beam of 60 GeV energy in a 3-pass racetrack configuration, as is illustrated in Fig. 2. This arrangement is outside the LHC tunnel and so it minimises any interference with the main hadron beam infrastructure. The electron accelerator may thus be built independently, to a considerable extent, of the status of operation of the proton machine. The chosen energy of 60 GeV, see Sect. 2.2, leads to a circumference U of the electron racetrack of 8.9 km. This length is a fraction $1/n$ of the LHC circumference, for $n = 3$, as is required for the e and p matching of bunch patterns. It is chosen also in order to limit the energy loss in the last return arc and as a result of a cost optimisation between the fractions of the circumference covered by SRF and by return arcs. As discussed below, that configuration is the default also for the FCC-he. The necessity to choose U to be a natural fraction of the proton accelerator circumference suggests to set $n = 11$ for the FCC case, which means an enlargement of the ERL racetrack circumference by 2 % when compared to the LHeC.

As Fig. 3 illustrates, it is possible to locate the LHeC electron beam tangentially to the LHC, at its inside, for *eh* collisions at IP2 after LS4. Recent considerations of the geological situation of possible IPs for FCC *he* collisions have lead to a tentative preference for an IR at point H. This location resides left to the far away IR for the second general purpose *hh* detector of the FCC. The LHeC ERL would possibly have to be upgraded and relocated to point H. There exists also a more speculative idea, see [10], of an 8-shaped ERL which could be tangential to both the LHC, at IP8, and the FCC at the expense of enlarged arcs for reaching down (and up) from the LHC to the lower FCC tunnel level.

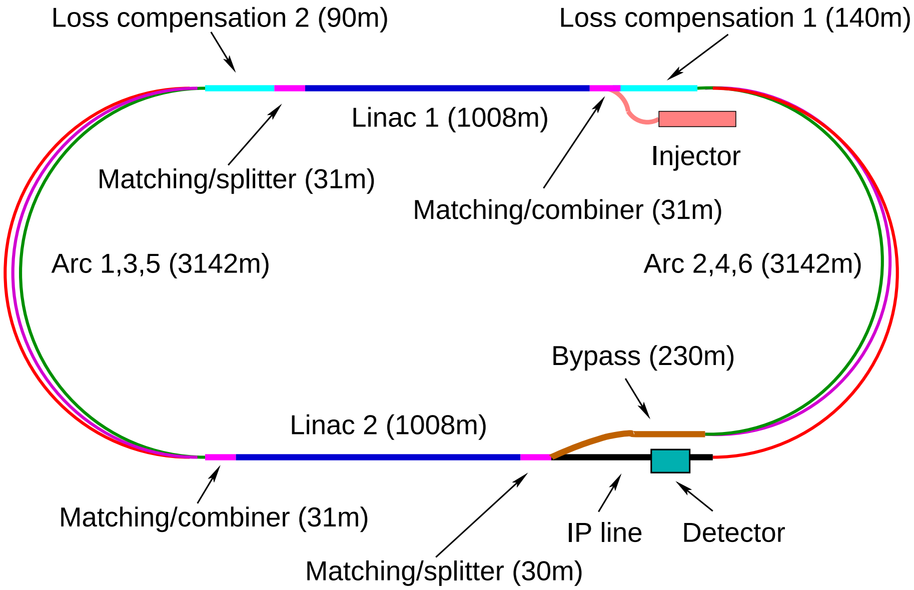

Figure 2: Schematic view of the default LHeC configuration. Each linac accelerates the beam to 10 GeV, which leads to a 60 GeV electron energy at the interaction point after three passes through the opposite lying linac structures made of 60 cavity-cryo modules each. The arc radius is about 1 km and the circumference chosen to be 1/3 of that of the LHC. The beam is decelerated for recovering the beam power after having passed the IP.

2.2 Choice of Electron Beam Energy for the LHeC

The choice of the default design electron beam energy E_e is dictated both by physics and by practical considerations. Physics wants it to be maximal, cost and effort prefer it to be rather small. From today's perspective, the *ep* and *eA* physics program has three cornerstones:

- **High precision Higgs SM and BSM physics** The cross section for Higgs production, in the reactions $ep \to \nu(e)HX$, is about proportional to the electron beam energy and the acceptance for forward going particles shrinks when the energy gets diminished: the potential for precision Higgs physics therefore rises more than linearly with E_e;
- **BSM and electroweak physics** A key example is top quark physics for which the LHeC has a unique potential both to find anomalous or flavour changing couplings and to perform salient high precision measurements. For $E_p = 7\,\text{TeV}$, the top production cross section in *ep* rises by a factor of ten when E_e increases from 30 to 60 GeV;
- **Novel QCD physics**, for which the discovery of gluon saturation would be a key example. That requires to cover the smallest possible Bjorken x values which are accessed with maximum energy, as x is decreasing with $s \propto E_p E_e$.

The racetrack LHeC footprint scales in its linac accelerator parts roughly in proportion to E_e , whereas the return arc radius scales like E_e^4, because of synchrotron radiation losses. One thus can achieve considerable gains in expenses if the energy was carefully chosen not to be too high [1].

2.3 Choice of Electron Beam Energy for the FCC-he

The FCC proton beam energy is projected to be 50 TeV, a seven-fold increase as compared to the LHC. This makes basically all physics arguments holding for the LHeC, sketched above, even stronger because Q^2 and $1/x$ are enlarged by nearly a factor of 10. The huge proton beam energy raises the question of the asymmetry of the electron-hadron beam energy configuration. Intuitively one would like to increase the electron beam energy as compared to the 60 GeV value chosen for the LHeC. One, however, needs to take into account how readily the cost for the electron beam goes beyond reasonable values when E_e rises. This is illustrated for the racetrack configuration in Fig. 4. The cost for the linac is proportional to E_e. The arc radii, however, scale $\propto E_e^4$, and in the current design are determined to allow for a fraction of about 1 % of synchrotron radiation energy loss. This implies a corresponding increase of cost for the magnets and also for the tunnel. The figure makes clear that doubling the energy results in nearly a factor of ten times higher total cost. A similarly high cost would result if one went for just a linac, with no recovery of power and consequently reduced luminosity [2]. One notices that the optimum number of turns may change when one went significantly away from the 60 GeV energy point for which 3 is optimum. At low energies more than 3 turns would reduce the linac cost while at large energies, beyond 100 GeV, less than 3 turns may lead to a better optimum. In any case, the cost for an electron beam of the FCC-he of energy above 100 GeV would become comparable to that for the ILC or the other FCC configurations. That could be considered in earnest only for spectacular, overriding physics reasons, such as the spectroscopy of now hypothetical leptoquarks of for example 5 TeV mass. A particular strength of the *ep* option in comparison to e^+e^- rests in the huge *ep* cms energy owing to the hadron beam at a similar cleanness of the interaction and the absence of event pileup which is a major concern for FCC-hh.

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[1] The choice of energy has to be made near to the realisation of the project. It is possible, for example, that new particles may still be discovered at the LHC which would set a clear threshold to be obeyed with the *ep* (or *eA*) collider, such as leptoquarks, demanding energies larger than 60 GeV for reaching say 1.5 TeV of LQ mass.

[2] A scheme with two head-on linacs for achieving TeV electron beam energies has also been considered [11] but would similarly require extraordinary funds.

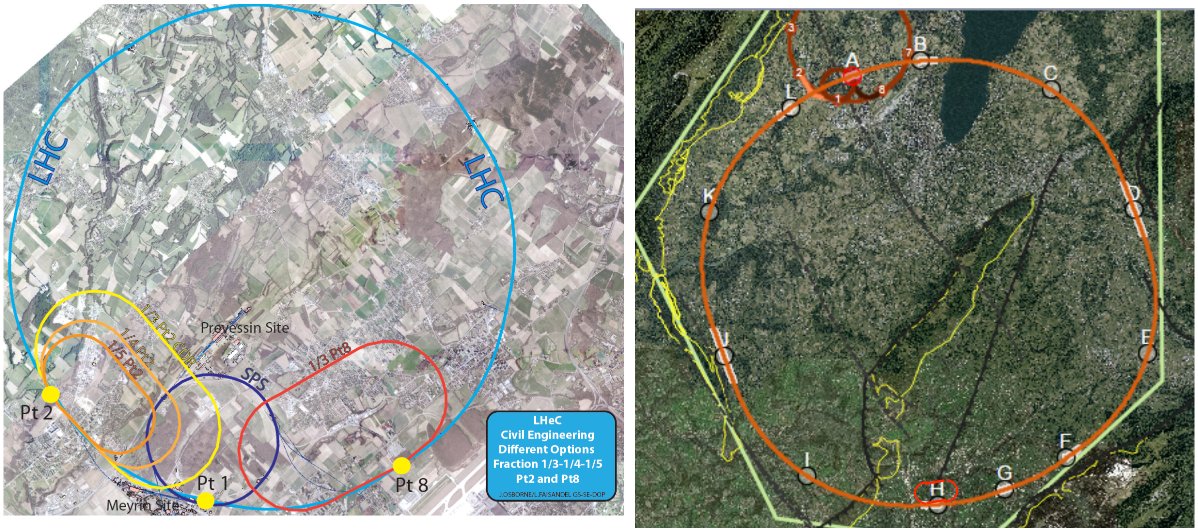

Figure 3: Possible locations of the ERL racetrack electron accelerator for the LHeC (left) and the FCC-he (right). The LHeC is shown to be tangential to Point 2 and Point 8. For Point 2 three sizes are drawn corresponding to a fraction of the LHC circumference of 1/3 (outer, default with $E_e = 60\,\mathrm{GeV}$), 1/4 (the size of the SPS, $E_e = 56\,\mathrm{GeV}$) and 1/5 (most inner track, $E_e = 52\,\mathrm{GeV}$). To the right one sees that the 8.9 km default racetrack configuration appears to be rather small as compared to the 100 km ring of the FCC. Geological considerations suggest a preference for Point H, left from Point G housing one of the large GPDs conceptually while location L may be a possibility too.

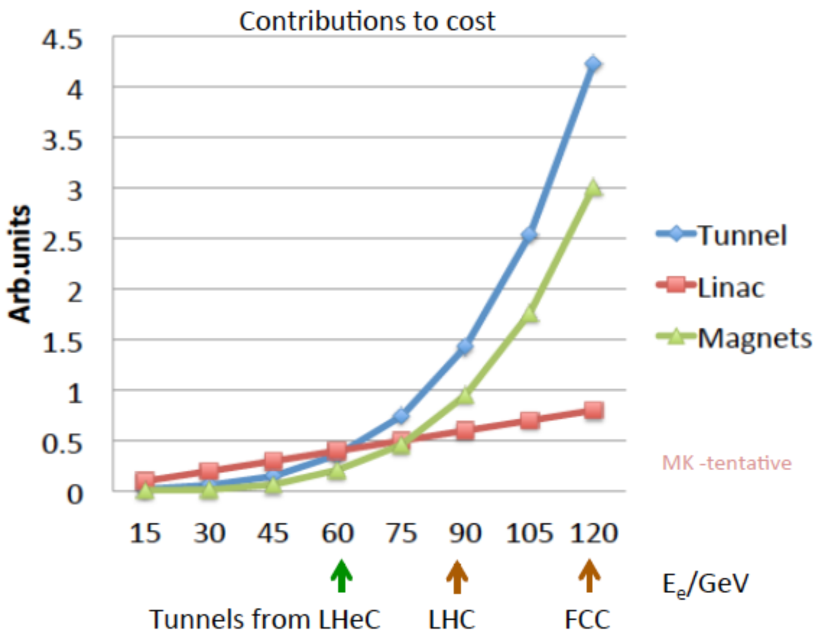

Figure 4: Sketch of the energy dependence of the core cost of the main components of the electron accelerator, in arbitrary units. The LHeC, designed to deliver $E_e = 60\,\text{GeV}$, has an about 8.9 km long tunnel for which linac and tunnel cost would be approximately equal and the magnet cost smaller. If one used a tunnel of the LHC size, triple the LHeC circumference, the tunnel cost would dominate while the linac and magnet costs would be comparable for achieving about 90 GeV. With a tunnel of the FCC size the linac becomes the smallest part of the cost. In fact for such energies one would most likely change the concept, leave the idea of an external racetrack ERL (see text) and perhaps come back to a ring-ring *ep* configuration, as had also been discussed in the LHeC CDR. Presently, however, it is not planned to house both the electron and proton machines in the FCC tunnel. The current default for *ep* is then a re-use of the LHeC electron beam, most likely relocated, and possibly refurbished with then higher quality RF.

The asymmetry in the beam energies poses a challenge to medium Q^2, high x measurements, which, however, would be covered first with the LHeC. The low Q^2 physics instead is better covered, if E_e was not chosen too high. This is illustrated in Fig. 5. It so is concluded that the ERL of the LHeC, providing a 60 GeV electron energy beam, may serve as the appropriate baseline for the conceptual design of the FCC-eh configuration. If indeed the LHeC was built prior to the HE-LHC or the FCC, ep collisions could be realised at very low cost from the start of these highest energy pp colliders.

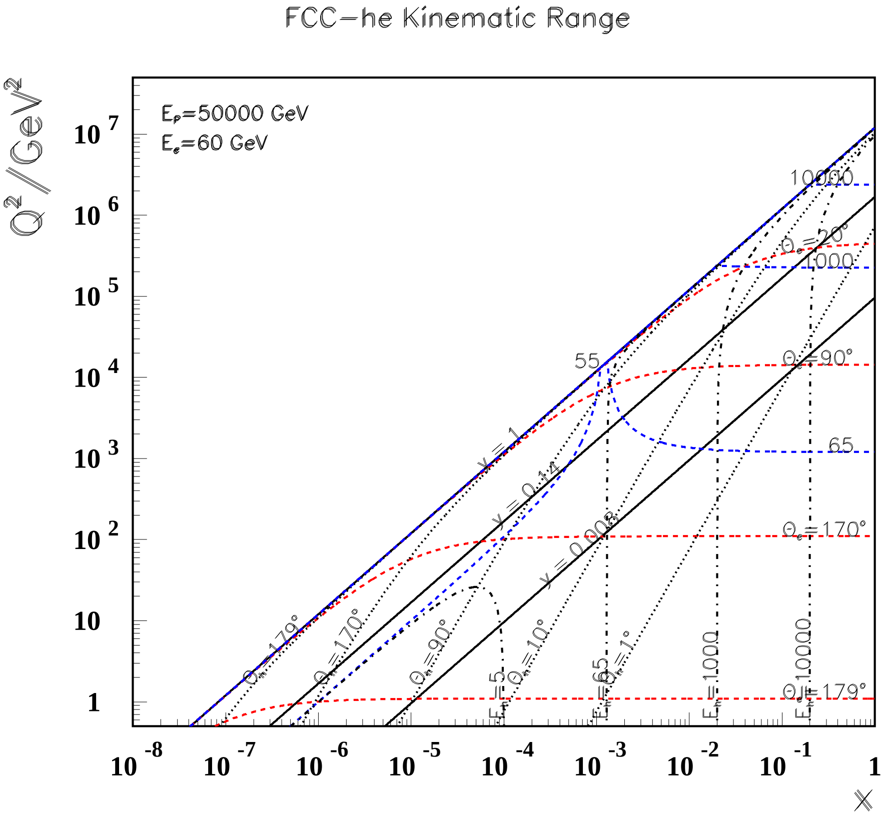

Figure 5: Kinematics of the FCC-he for $E_p = 50\,\mathrm{TeV}$ and $E_e = 60\,\mathrm{GeV}$. Blue dashed: lines of constant scattered electron energy, which for Q^2 below $1000\,\mathrm{GeV}^2$ never exceeds 65 GeV. Red dashed: lines of constant electron polar angle. One observes that the low x region is very well accessible with a detector acceptance to backward electrons down to one degree. Black dashed-dotted: lines of constant hadronic final state energy. At large Borken x, energies of up to tens of TeV are scattered in the forward detector region; Black dotted: lines of constant polar angle of the hadronic final state. One can see that the high x, medium $Q^2 \sim 10^{3-4}\,\mathrm{GeV}^2$ region is hardly accessible with the FCC-he, it yet would have been covered by the LHeC before.

3 Parameters

3.1 Luminosity Estimate for Future ep Colliders at CERN

The luminosity L of the LHeC as of the FCC-he, in a simplified model, is given by the following formula

$$L = \frac{N_p N_e f \gamma_p}{4\pi \epsilon_p \beta_p} \cdot H_{geom} H_{b-b} H_{coll} \tag{1}$$

Here, N_p is the number of protons per bunch and ϵ_p and β_p are the proton emittance and beta-functions. We assume that the proton beam parameters N_p and ϵ_p are defined by the main experiments that collide protons off protons because the default assumption is one of concurrent *ep* and *pp* operation. For the proton beta-function in the electron-proton collision point we assume a challenging target value of $\beta_p = 15$ cm. This may be achievable because only one proton beam needs to be focused, which is a simplification compared to the proton-proton case. $f = 1/\Delta$ denotes the bunch frequency, which for the default bunch spacing of $\Delta = 25\,\mathrm{ns}$ is= 40 MHz.

N_e is the number of electrons per bunch which determines the electron current $I_e = eN_ef$. The electron current for HE-LHC and FCC-eh is assumed[3] to be $I_e = 20$ mA, a slight increase compared to the 15 mA assumed for the LHeC in the HL LHC phase and triple the value of 6.4 mA used in the LHeC CDR. This will yield a total synchrotron radiation of about 40 MW in the return arcs. To compensate for this power loss through the beam, a grid power of the order of 65 MW may be required. A value of 20 mA is nowadays already in reach or has even been surpassed with intense DC photocathodes. Since, however, a cavity has to stand the sixfold of I_e due to the (de)acceleration in three turns one should be careful in choosing I_e not to be too large.

Table 1: Baseline parameters and estimated peak luminosities of future electron-proton collider configurations for the electron ERL when used in concurrent *ep* and *pp* operation mode.

parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	12.5	50
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	1.3	1.3	1.7	3.5
bunch spacing [ns]	25	25	25	25
protons per bunch [10^{11}]	1.7	2.2	2.5	1
$\gamma\epsilon_p$ [μm]	3.7	2	2.5	2.2
electrons per bunch [10^9]	1	2.3	3.0	3.0
electron current [mA]	6.4	15	20	20
IP beta function β_p^* [cm]	10	7	10	15
hourglass factor H_{geom}	0.9	0.9	0.9	0.9
pinch factor H_{b-b}	1.3	1.3	1.3	1.3
proton filling H_{coll}	0.8	0.8	0.8	0.8
luminosity [$10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	1	8	12	15

The factors H_{geom}, H_{b-b} and H_{coll} are geometric correction factors with values typically close to unity. H_{geom} is the reduction of the luminosity due to the hourglass effect, H_{b-b} is the increase of the luminosity by the strong attractive beam-beam forces and H_{coll} is a factor that takes the filling patters of the electron and the proton beam into account. Estimates for these parameters are shown in Tab. 1. Unless discussed above, further parameters used for the four *ep* collider configurations considered can be found i) for the LHeC as evaluated in its conceptional design in Ref. [5], ii) for the high luminosity version of the LHeC in Refs. [12, 13, 8], iii) for the energy doubler of the LHC, the HE-LHC in Refs. [14, 15] and for the FCC-he in Ref. [14, 15]. One observes that compared to the CDR of the LHeC from 2012, it seems possible to achieve peak luminosities near to or larger than $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, which makes these future *ep* colliders most exciting and efficient machines for the study of new physics at the accelerator energy frontier.

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[3] The numbers quoted hold for unpolarised electron beams. One may currently expect a polarised electron source to provide half of that current which requires further developments as are ongoing for weak interaction measurements such as at MESA. In order to achieve luminosities of order 10^{33} with positrons significant developments are required. For positrons dedicated operation at very high luminosity may be a particularly attractive option as the loss in lepton intensity is compensated by a gain in proton and operation performance as indicated below.

3.2 Simulation of the FCC-eh Performance

For the FCC-hh, two different parameter sets have been defined, the baseline and the ultimate set. Hence we give parameters for the baseline and comment on the ultimate set also. It should be noted that the FCC proton beam parameters vary during a run. The protons emit synchrotron radiation, which reduces their emittance ϵ_p. Their number, N_p, decreases as they are destroyed colliding in the main experiments. Hence the proton beam size and intensity change during the run, which leads to a weak variation of the luminosity.

The electron current is distributed into bunches with a default spacing of 25 ns, leading to $N = 3 \cdot 10^9$ particles per bunch. Studies of the beam stability showed that a charge of $N = 4 \cdot 10^9$ is still stable.

The electron beta-function and the position of the electron beam waist are the a result of the overall optimisation of the collision that affect the product $H_{geom}H_{b-b}$. This optimisation is dominated by the strong beam-beam forces. In general, smaller electron emittance lead to larger luminosity.

The electron beam emittance from the source can be of the order of $\epsilon_e \approx 1$ μm. In the arcs of the recirculating electron linac, the horizontal emittance will increase by about 7.5 μm and only by 0.8 μm in the vertical. We set a target of $\epsilon_e = 10$ μm at the collision point in both planes. The possibility to collide with flat electron beams remains to be studied.

The collision of the two beams has little impact on the proton beam. The electron bunch charge is quite small and the proton energy is high. However, the electron beam is strongly affected by the proton beam. The proton bunch contains a large number of particles and the electron energy is not very high. During the collision the electron bunch is focused by the protons, which leads to an important reduction of the transverse electron beam size. As a consequence the luminosity is larger than for rigid beams. Also, the conventional matching of the sizes of the two beams would not work because the electron bunch size is changing by a factor of two or so during the collision. Hence, we simulated the beam-beam effect with GUINEA-PIG [16]. We varied the longitudinal position of the waist and the beta-functions for optimum luminosity.

Finally, the factor H_{coll} is given by the fraction of electron bunches that collide with a proton bunch. Only 80% of the FCC-hh circumference is filled with proton bunches, hence 20% of the electron bunches will not collide with a proton bunch. This leads to a collision factor $H_{coll} = 0.8$. Depending on the filling pattern of the proton ring it could be possible to use an electron beam bunch pattern that has no bunches in non-colliding positions. This would reduce the rate of electron bunches by 20 % and allow to increase their charge by 25 %. The luminosity would increase by 25 %. However, we do not assume this option in the baseline. Accelerating the non-colliding bunches may be useful for limiting the fluctuations of the RF power stored into the linacs. A small fraction of non-colliding bunches is known to be of interest also for the understanding of backgrounds and the detector response. The bunch distribution of the electron beam could be affected by another process. The electron beam ionises the rest gas in the linacs and arcs. The positive ions may then be trapped in the electron beam which can lead to an instability [5]. The instability can be suppressed by introducing a gap in the electron beam. During the passage of this gap the ions will be lost [5].

The result of the simulation study is summarised in Tab. 2. They are in good agreement with the rough estimate presented above (Tab. 1).

3.3 Dedicated ep Operation

There could be an interest in dedicated *ep* operation because one readily observes possible significant gains in the instantaneous and integrated luminosity performance: A first estimate hints to a possibly 10 fold higher proton beam brightness and a reduced beta function, by perhaps a factor of two, with only one beam present and squeezed and less aperture constraints. A factor of two may also be

Table 2: Parameters and estimated peak and integrated luminosities of the FCC-he, when the 50 TeV proton and the 60 GeV ERL electron beams collide, in an operation mode where simultaneously *pp* data may be taken.

Parameter	unit	protons	electrons
Beam energy	GeV	50000	60
Normalised emittance	μm	$2.2 \rightarrow 1.1$	10
IP betafunction	mm	150	$42 \rightarrow 52$
Nominal RMS beam size	μm	$2.5 \rightarrow 1.8$	$1.9 \rightarrow 2.1$
Waist shift	mm	0	$65 \rightarrow 70$
Bunch population	10^{10}	$10 \rightarrow 5$	0.31
Bunch spacing	ns	25	25
Luminosity	$10^{33}\text{cm}^{-2}\text{s}^{-1}$	$18.3 \rightarrow 14.3$	
Int. luminosity per 10 years	[ab^{-1}]	1.2	

obtained from the much enhanced operation efficiency in dedicated mode, mainly because the proton beam lifetime would be hugely increased without *pp* collisions, which lead to $\tau_p < 5$ h. Therefore, dedicated *ep* runs could be typically a day long, and overall, in dedicated mode, luminosities in excess of O(10^{35}) cm^{-2}s^{-1} appear to be not unrealistic. An integrated luminosity of 1 ab^{-1} annually would be possibly to achieve. Such a scenario could be specially relevant for taking a large amount of positron-proton data in not a too long period of operation, since the e^+ currents will be much lower, by one or even two orders of magnitude, than the e^- currents.

4 Electron-Ion Collisions

The CERN ion beams of the LHC, the HE-LHC and the FCC provide a unique base for high energy, high luminosity deep inelastic electron-ion scattering physics. Since HERA was confined to protons only, the FCC-eh (LHeC) extends the kinematic range in Q^2 and $1/x$ by 5 (4) orders of magnitude which is a huge increase in coverage set to change the understanding of parton dynamics in nuclei and of the formation of the quark gluon plasma radically. At the same time one should note that the hadron beams may operate also at injection energy and the electron beam at low energy also. Therefore the LHeC as an EIC covers also the kinematic range of the low energy electron-ion colliders currently under consideration in the US and in China. Based on the intense CERN hadron beams and the default 60 GeV electron ERL, an initial set of parameters in the maximum energy configuration has been determined [15] which is listed in Tab. 3.

5 Summary

Table 1 summarises the current choices of the parameters for the available energy frontier *ep* collider configurations at CERN. All are based on the racetrack, multi-turn ERL as the default choice for the electron accelerator, and in each case it is assumed that *ep* and *pp* were operated at the same time. The ERL technology is worldwide under intense development and a design concept is about to be published [9] for demonstrating the main choices of the specific ERL configuration which is the base for the here sketched *ep* colliders.

Table 3: Baseline parameters of future electron-ion collider configurations based on the electron ERL, in concurrent eA and AA operation mode.

parameter [unit]	LHeC (HL-LHC)	eA at HE-LHC	FCC-he
E_p [TeV]	0.57	1.02	4.1
E_e [GeV]	60	60	60
$\sqrt{s}$ nucleon pair [TeV]	0.8	1.1	2.2
bunch spacing [ns]	25	25	25
nr of bunches	592	592	2215
ions per bunch [10^8]	1.2	1.2	1.2
$\gamma\epsilon_A$ [μm]	1.5	1.0	0.9
electrons per bunch [10^9]	2.3	3.0	3.0
electron current [mA]	15	20	20
IP beta function β^*_A [cm]	7	10	15
hourglass factor H_{geom}	0.9	0.9	0.9
pinch factor H_{b-b}	1.3	1.3	1.3
proton filling H_{coll}	0.8	0.8	0.8
luminosity [$10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	5	12	37

The LHeC was originally designed to achieve about $10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ luminosity. With the discovery of the Higgs boson an update to increased luminosity had been initiated which is under way. Using the HL-LHC and increasing I_e at somewhat diminished β_p moved the luminosity to close to10^{34} and an integrated luminosity of O(1) ab^{-1} appears as realistic, ultimate goal for a decade of LHeC operation.

If the HE-LHC was built, it would boost the ep cms energy of the LHeC to nearly 2 TeV, beyond the acceptance limit for leptoquarks at the LHC. The luminosity would be as large as 10^{34}. For the FCC-he the parameters as discussed above would enable a peak luminosity of O(10^{34}) too. An interesting option is the possibility to achieve luminosities of O(10^{35}) in dedicated ep operation with enhanced efficiency for the proton beam lifetime would not be reduced by pp collisions.

If the FCC was operated in the ultimate mode, N_p would be reduced by a factor of 5 but the emittance by more than fivefold also, such that the proton beam brightness stayed about the same. If for the ultimate FCC-pp the bunch spacing was kept at 25 ns one thus would also reach $L\ = \mathrm{O}(10^{34})$. Lower values came out, however [14], if $\Delta = 5\,\mathrm{ns}$ was chosen, as is an option for limiting the high pile-up in pp interactions.

The LHeC and its successor, the FCC-he, would represent the most powerful, high resolution microscopes of matter the world could construct. These had a unique DIS and Higgs physics programme. Moreover they made the LHC and later the FCC-hh complete and enabled precise measurement leading much beyond our present understanding of nature. The luminosity potential is a factor of 1000 larger than that of HERA, which make the CERN based energy frontier ep and eA colliders an exciting subject for further study.

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