PROCEEDINGS OF SCIENCE

Energy Frontier DIS at CERN LHeC and FCC-eh

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The Large Hadron-electron Collider (LHeC) at CERN is a design study in the context of the LHC luminosity upgrade project, HL-LHC, to establish electron-proton/nucleus collisions with centre-of-mass energies in the TeV regime and luminosities in the order of $10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$. It implies the construction of an energy recovery linac in racetrack configuration to provide an intense 50 GeV electron beam that will collide with the HL-LHC hadron beams. Such an energy recovery racetrack could also be used at the Future Circular Collider, the FCC-eh, with even higher centre-of-mass energies and similar luminosities. We will review the status of the project with focus on the accelerator design progress, based on the updated thorough LHeC design report, published in March 2020.

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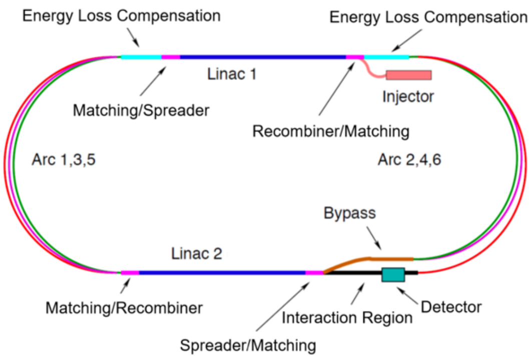

Figure 1: Sketch of the ERL geometry, using two sc. linear accelerators, connected by return arcs.

Parameter	Unit	Value
Beam energy	GeV	50
Bunch charge	pC	499
Bunch spacing	ns	24.95
Electron current	mA	20
trans. norm. emittance	μm	30
RF frequency	MHz	801.58
Acceleration gradient	MV/m	20.06
Total length	m	6665

Table 1: ERL main parameters

1. Introduction

The LHeC project studies the design of an intense, high energy electron beam to collide with the protons of the LHC storage ring and aims for an integrated luminosity of about 5 ab^{-1}. The design of the machine is described in detail in the updated version of the LHeC design report [1]. It is based on two super-conducting linacs of about 900 m length, which are placed opposite to each other and connected by three return arcs on both sides. A final electron beam energy of 50 GeV is reached in this 3-turn racetrack energy recovery (ERL) design. This configuration allows to keep the overall energy consumption on a modest level for up to 20 mA stored electron current. The main parameter list of the LHeC is shown in Tab. 1.

2. Layout of the ERL

The layout of the ERL is sketched in Fig. 1. The total length corresponds to 1/4 of the LHC circumference and is determined by the reachable beam energy, due to the synchrotron radiation emitted in the return arc dipoles. Each of the two linacs provides an accelerating voltage of 8.25 GV, which after three turns adds up to the design electron energy of 50 GeV. After acceleration in the linacs, the beam is guided into three return arcs, that are optimised for the corresponding beam energy. A total of 352 horizontal bending dipoles are combined in three apertures for the three energy steps of the beam. They are stacked vertically to guarantee the ideal path length needed for stable arrival time with respect to the Linac's RF phase.

2.1 RF System & Linac Structure

The RF structure of the Linacs is based on super conducting (sc.) five-cell cavities operating on a frequency of 800 MHz. Following the basic design of the resonators of the SPL study [2], a first prototype test started in collaboration with JLAB. The cavity quality factor, Q_0, measured in a vertical test stand as a function of the acceleration gradient is plotted in Fig. 2. The required acceleration gradient of 20.06 MV/m lies comfortably within the technical performance of the cavity [3]. For the focusing structure of the Linacs a standard FoDo lattice has been chosen. Due to the increasing energy over the three turns, the electron beam will travel through the lattice with

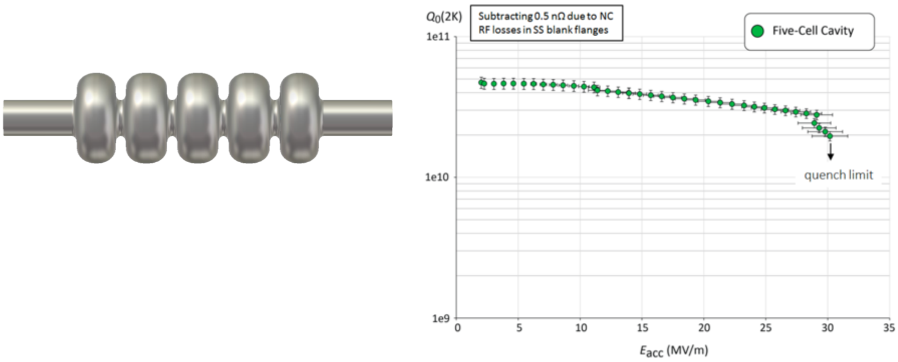

Figure 2: Prototype of the super conducting 5 cell cavity and measured quality factor.

different beam rigidity. Therefore a flexible focusing structure had to be found to allow a successful re-matching of the linac optics to the three return arcs. Dispersion suppressors and matching sections combine the Linac optics with the arcs on either side of the machine (see Fig. 3).

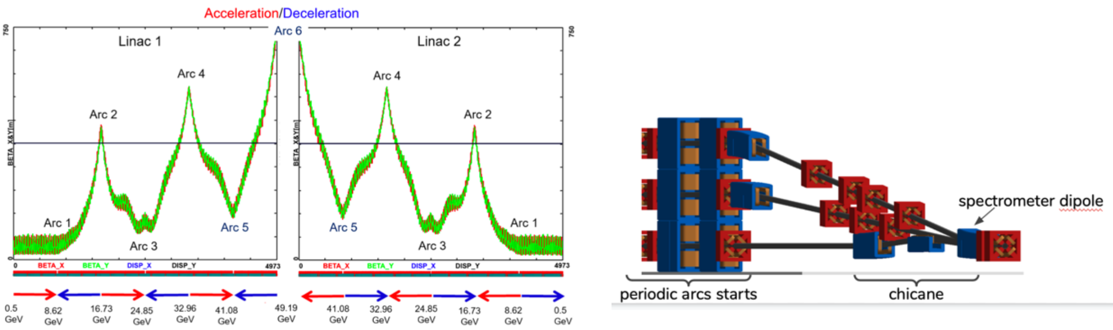

Figure 3: Optics functions in the linacs (left): Dispersion suppressor and matching section are connected on both sides to the arc structures via spreader/re-combiner modules (right).

2.2 Spreader & Re-combiner

At the end of the Linac, the beam has to be guided into the return arc that corresponds to the beam rigidity at the given acceleration step. A combination of dipoles and quadrupole magnets provides the vertical bending and adapts the beam optics to the arc structure. This “spreader" (in front) and “re-combiner" (after the arc) represent a non-dispersive deflecting system to provide the necessary vertical off-set between the three arc modules (Fig. 3).

3. Interaction Region

The Interaction Region (IR) of the ERL is one of the most challenging parts of the machine: While seeking for highest luminosity in ep-collisions, which includes strong mini-beta structures for both beams, the colliding beams have to be separated and guided to their lattice structures, to avoid parasitic bunch encounters. In addition, collisions and beam-beam effects with the second non-colliding proton beam have to be avoided.

3.1 Proton Beam Optics

The encounters with the non-colliding proton beam are avoided by a proper location of the new interaction point (IP). Shifted in position and thus in time, direct collisions between the two proton beams as well as with the electron beam can be excluded. Long range encounters are suppressed by a large crossing angle of 7 mrad. The optics of the colliding proton beam follows the standard settings of the HL-LHC. Fig. 4 shows the proton optics for values of β=7 cm at the interaction point of the LHeC. The long-ranging beta-beat which is an essential feature of the HL-LHC optics [4] is clearly visible on both sides of the IP.

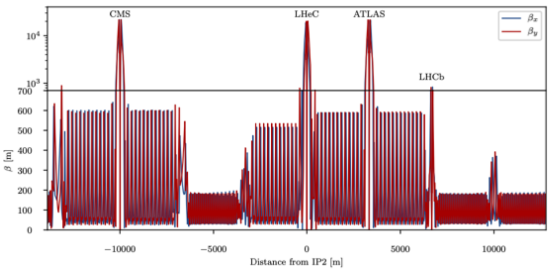

Figure 4: LHC proton beam optics, optimised for the LHeC design values of β=7 cm at the LHeC IP.

3.2 Electron Beam Optics and Separation Scheme

The design of the IR has to take a manifold of conditions into account: Focus the electron beam to the required β values in both planes, establish sufficient beam separation, optimise the beam separation for smallest critical energy and synchrotron light power, and leave sufficient space for the detector hardware. A separation scheme has been established [5] that combines these requirements in one lattice structure (see Fig. 5). Due to the different rigidity of the beams, a separation is possible by applying magnetic fields: The spectrometer dipole of the LHeC detector, named *B0* in the figure, is used to establish a first separation. Right after and as close as possible to the IP, the mini-beta quadrupoles of the electron beam are located. They provide focusing in both planes for matched beam sizes of protons and electrons at the IP: $\beta_x(p) = \beta_x(e), \beta_y(p) = \beta_y(e)$. On top of that they are positioned off-center with respect to the electron beam, thus acting as combined function magnets to provide the same bending radius as the separator dipole: A quasi constant, soft bending of the electron beam is achieved throughout the magnet structure. Additional conditions were put for a reduced beam size of the electron beam at the location of the first proton quadrupole. At this position, L^*=15 m, the reduced electron beam size leads automatically to a minimum of the required beam separation and as direct consequence to smallest synchrotron radiation effects. The optical functions of the electron beam in this optimised interaction region are shown in Fig. 6.

3.3 Synchrotron Light

The synchrotron light parameters, i.e. critical energy, radiation power and the geometry of the emitted light cone were determined with the simulation code BDSIM [6]. As expected, the synchrotron light conditions in the arcs become more serious turn by turn, reaching the highest level in the return arc after the collision point. The values are summarised in Tab. 2. Special

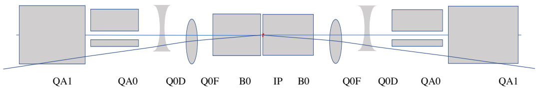

Figure 5: Schematic view of the combined focusing - beam separation scheme

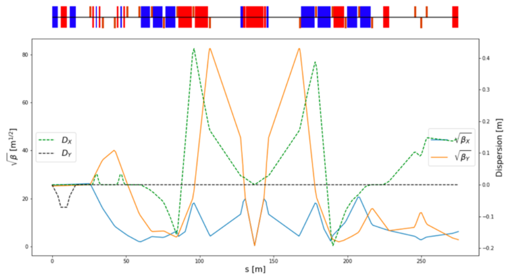

Figure 6: Optical functions of the electron beam in the IR.

care is needed in the vicinity of the particle detector. The properties of the focusing elements, the separation scheme and the geometry of the Interaction Region (IR) have been optimised for smallest critical energies and power of the emitted light. Fig. 7 summarizes the results. The graph shows the

Arc	Energy (GeV)	Crit. Energy (keV)	Power (MW)
1	8.75	3.2	0.01
2	17.00	23.9	0.21
3	25.25	78.5	0.75
4	33.5	183.3	2.45
5	41.75	354.8	5.87
6	50.0	609.3	12.17

Table 2: Critical energy and power of the emitted synchrotron light in the return arcs of the ERL.

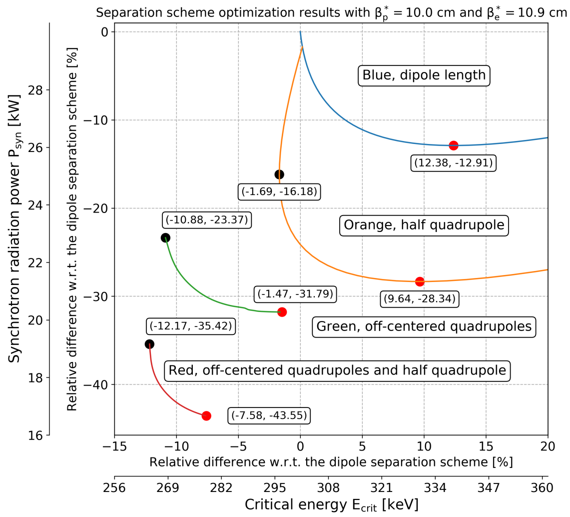

Figure 7: Optimising the synchrotron light for lowest critical energy and power, details in the text.

reduction of the critical energy and power due to the different steps of the optimisation procedure. Starting from a pure separator dipole design to establish the required beam separation, the concept of a half-quadrupole as first focusing element in the proton lattice is introduced as well as an improved beam separation of the electrons by off-centre quadrupoles. The actual distribution of the detector dipole field and the off-centre quadrupoles has a considerable effect: The red and black points in the graph correspond to the minimum achievable critical energy and emitted power, respectively. Dedicated calculation of the synchrotron light cone and a sophisticated machine detector interface including absorbers will be needed to shield the detector parts and accelerator modules.

3.4 Beam-Beam Effects

The beam-beam effect will always be the final limitation of a particle collider and care has to be taken, to preserve the beam quality and limit detrimental effects on the emittance to assure a successful energy recovery process in the ERL. In order to minimise the effect, the optical functions at the IP have been re-optimised, taken into account the influence of the beam-beam force. In Fig. 8 the situation is represented in the (x,x') phase space. While tails in the transverse beam distribution as consequence of the beam-beam effect are clearly visible, the core of the beam still remains in a quasi ellipse like boundary. The coordinates obtained are used as starting conditions for the deceleration part of the ERL for a full front-to-end simulation.

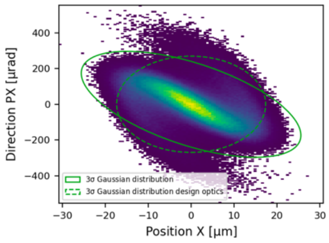

Figure 8: Simulation of the beam-beam effect for the electrons plotted in phase space coordinates, x,x'.

4. Conclusion

The LHeC will provide collisions between electrons from a recirculating linac and the protons of the LHC with luminosities in the order of 10^{34} cm^{-2} s^{-1}. The basic layout of the machine has been optimised and the ERL design as concept allows for highest stored electron currents. The optics of the linacs, the return arcs and the interaction region have been optimised for smallest emittance growth and highest beam quality throughout the complete ERL process. In front-to-end simulations, as next step, the overall performance will be studied with main focus on the efficiency of the energy recovery process and the mitigation of synchrotron radiation background in the Interaction Region.

References

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