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FRONT-TO-END SIMULATIONS OF THE ENERGY RECOVERY LINAC FOR THE LHeC PROJECT

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Abstract

The LHeC project aims to study electron-proton deep inelastic scattering at the TeV energy scale with an innovative accelerator program. It exploits the promising energy recovery technology in order to collide an intense 50 GeV lepton beam with one hadron beam from the High Luminosity Large Hadron Collider (HL-LHC) in parallel to the hadron-hadron operation. The paper presents the studies that have been performed to assess the performance of the machine and the efficiency of the energy recovery process for different scaling of the ERL. The studies include emittance blow up due to synchrotron radiation emission and beam-disruption created by the strong beam-beam force at the interaction point. The design principles of the ERL structure are discussed, including the particle detector bypass and the interaction region, and the results of the tracking simulations are presented, considering the complete multi-turn ERL process. Special attention is turned to the lepton beam emittance budget and the resulting energy recovery performance.

INTRODUCTION

The LHeC project foresees a multi-turn energy recovery linac for the production of a high power electron beam colliding with one LHC proton beam. The interest in the energy recovery technology comes from the limited power consumption of the machine, around 100 MW, for a luminosity of about 1×10^{34} cm^{-2} s^{-1} in CW operation mode. The high luminosity can be reached with a large disruption of the electron beam at the interaction point, similar to what is proposed for a linear collider. The challenge being that the heavily disrupted electron bunch will need to perform successive deceleration in order to recover the energy and effectively reduce the power consumption of the accelerator. The studies assess the energy recovery efficiency of several ERL circumferences and their limitations. A more detailed introduction to the machine challenges of the LHeC project and its relation with FCC-eh and PERLE is given in [1].

DESIGN PARAMETERS

A summary of the design parameters is presented in Table 1, a more detailed parameter list can be found in [2]. It features the HL-LHC proton beam parameters in which the bunch spacing is 25 ns and a number of colliding bunches of 2760 or 2744 [3] since one needs empty bunches for the multiple kickers rise times in the injectors and for the dump. The bunch spacing in the ERL is assumed to be 25 ns to match the bunch structure of LHC. Nevertheless empty bunches might be required for ion clearing gaps.

Table 1: Design Parameters for the LHeC Project

Parameter	Unit	Proton	Electron
Beam energy	GeV	7000	50
Bunch intensity	10^{11}	2.2	0.03
$\gamma\varepsilon_{x,y}$ at IP	mm mrad	2.5	30
$\beta_{x,y}$ at IP	cm	10.00	10.92
Bunch length σ_s	mm	75.5	0.6
b-b parameter ξ	-	1.5×10^{-4}	1.64
Geometric $\mathscr{L}$	cm^{-2} s^{-1}	6.5×10^{33}	

A luminosity of about 1×10^{34} cm^{-2} s^{-1} could be achieved by taking advantage of the electron pinching effect and by increasing the electron beam current. It can be specified that the injection in the ERL will take place at 500 MeV unlike the injection energy for the PERLE project at 7 MeV. Therefore the LHeC will require a different injector design with respect to the one currently under investigation for PERLE.

ERL LAYOUT

The RF of the linac runs at 801.58 MHz in order to have a bucket matching with LHC, moreover, the linac optics design minimises the effect of the wakefields such that the lowest energy must have the minimum beta function according to the following merit function:

$$\text{merit function} = \oint \frac{\beta}{E}\, ds. \tag{1}$$

Besides, the arcs optics have two different optimisations, the first one being for the three lowest energies with a minimum/flexible momentum compaction factor, while the arcs of the three highest energies minimise the emittance growth due to the emission of radiation that scales with the $\mathscr{H}$-function.

$$\mathscr{H} = \gamma D^2 + 2\alpha DD' + \beta D'^2 \tag{2}$$

where α, β, γ are the optical Twiss functions and D, D' the dispersion function and its derivative. The spreaders/combiners connect the linac structure to the arcs and route the electron bunches according to their energies. The design has been modified reducing to one step the vertical deflection such that the bending radius is increased and therefore the vertical emittance growth is mitigated. The interaction region has been successfully optimised in order to obtain the minimum synchrotron radiation light in the detector environment as well as in the superconducting magnets of the

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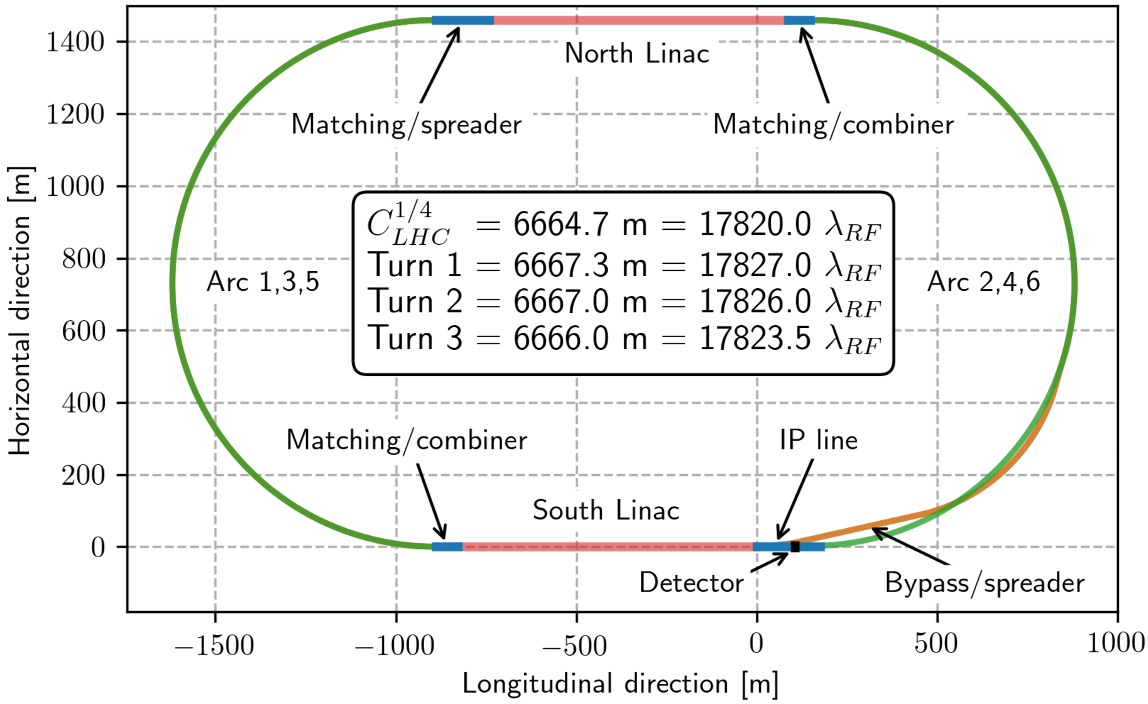

Figure 1: Layout for the 1/4 LHC circumference ERL representing the different sections composing the machine.

proton mini beta structure. The interaction region features a dipole embedded in the particle detector that allows head-on collision. It is followed by a doublet of quadrupoles that are off-centered in order to participate to the separation scheme as well as to relax the electron focusing structure further away from the IP. A normal conducting half quadrupole completes the separation scheme, only influencing the proton lattice in order to replace part of the first superconducting quadrupole in the separation scheme. More details on the interaction region optimisation can be obtained in [4].

The particle detector bypass provides sufficient horizontal separation such that the beam leaves the linac structure and reaches a 10 m horizontal separation from the interaction point in order to leave space for the detector and potential shielding materials. The combination of long dipoles and a minimal $\mathcal{H}$-function in the detector bypass minimises the impact of the extra synchrotron radiation emitted in this section. The layout of the ERL is presented in Fig. 1.

TRACKING OF THE ERL

The tracking of the ERL has been studied with PLACET2 software [5] and features the Incoherent Synchrotron Radiation (ISR) and the weak strong beam-beam interaction at the interaction point (IP). The studies will show the emittance budget required for several circumferences that are discussed for the basic machine layout and the achieved transmission. The parameters used for the tracking simulations are listed in Table 1.

The optics design of the multi turn ERL is shown in Fig. 2 and present the sequence of linacs and arcs leading to the interaction region with a large vertical beta function. The other spikes take place in the matching section joining the linac optics to the periodic arc optics. The tracking takes place over three acceleration turns until the IP and three deceleration turns. The lattice is composed of the two linacs as well as second harmonic RF cavities in order to compensate the losses in the arcs. The phase shift necessary to enter in a decelerating phase in the cavities happens in the highest energy arc where the third turn is a ratio of the LHC circumference with an additional 3.5 RF wavelengths.

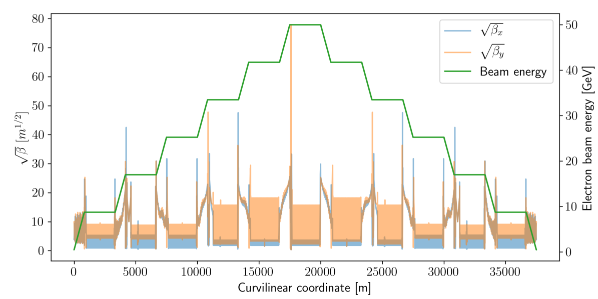

Figure 2: Representation of the beta functions and the beam energy along the multi-turn ERL operation.

Synchrotron Radiation in the ERL

The synchrotron radiation for each ERL circumference varies significantly and therefore the number of extra cavities to compensate the losses in the arc too. The electron beam energy has been reduced from 60 GeV to 50 GeV allowing

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smaller scale ERL with an equivalent beam quality for a considerable impact on the cost of the machine.

The emission of radiation in the arcs greatly affects the horizontal emittance growth and sets a boundary on the maximum injection emittance that can be accepted in the machine in order to meet the required beam size at the IP.

The results of the tracking simulation give emittance growths that agree with the analytical calculations during the acceleration turns. After the interaction region the particles increasingly gain energy spread that creates an optics mismatch and extra emittance growth that ultimately leads to beam losses as the deceleration goes on. The emittance growth results for the 1/3 of LHC circumference can be found in Fig. 3.

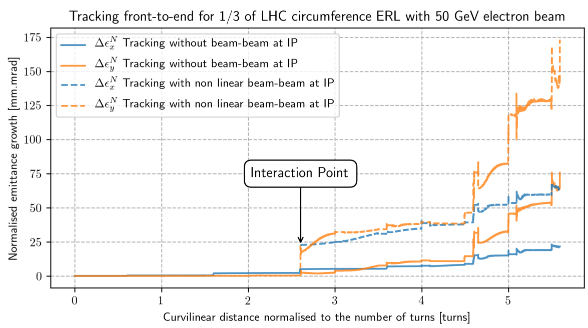

Figure 3: Emittance growth along the curvilinear coordinate for the 1/3 of LHC circumference ERL design.

Beam-Beam Optimization

The beam-beam optimisation of the interaction between the HL-LHC proton bunch of 7 TeV and the 50 GeV electron beam has been simulated with a weak strong simulation of which the electron bunch represents one slice of the proton bunch. This study led to the observation of a maximum for the luminosity that is also a minimum for the emittance growth for a specific set of Twiss parameters at the interaction point. A gain around 14% in luminosity with a negligible emittance growth is obtained compared to the optical matching, *i.e.* the matching of the electron transverse beam size with the proton beam size at IP. The optimal settings have a smaller beta function at the interaction point (9 cm vs. 10.9 cm originally) combined with a waist shift of 40 mm. The phase space distortion is also mitigated compared to the original design. Nevertheless the drawback is that a capture optics (see Fig. 4) on the post collision side of the interaction is necessary to optimise the beam quality during the deceleration and ultimately the transmission until the beam dump. The luminosity optimisation also requires more aperture in the quadrupoles since the beta function at the waist is 4.4 cm due to the waist shift and the pinching effect of the proton. Further studies are needed regarding the impact of a smaller beam size at the IP on the optimal separation scheme.

The beam-beam effect on the proton bunch remains in the shadow of the other effects and is considered as not critical. A careful alignment of the electron bunch at IP will

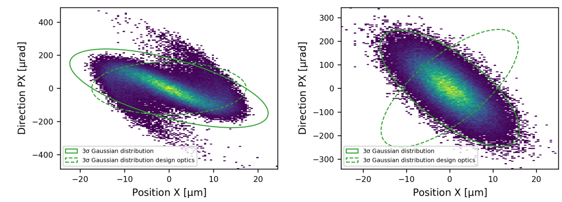

Figure 4: Phase space electrons distribution post collision. Left: Optical matching with HL-LHC proton beam. Right: Luminosity optimum settings.

be necessary as it could lead to undesirable proton emittance growth [2].

Tracking Results for Several ERL Circumferences

A normalised transverse emittance of 30 mm mrad at the collision point is obtained for each design by adjusting the injection emittance. The tracking allows to compare the injector constraints in terms of emittance for several designs as well as their attainable energy recovery efficiencies. The vertical emittance is not shown since there is an increase of 1.5 mm mrad until the IP due to the same spreader/combiner contributions.

As expected the smallest ERL circumference requires a smaller horizontal injection emittance that will potentially not allow enough margin for further studies including magnet field errors and misalignment (see Table 2). It is clear that the energy recovery efficiency is strictly set by the energy lost in the arcs that is compensated by extra RF cavities placed along the ERL. The beam losses occur in the last deceleration stages not impacting the energy recovery but would require further study in terms of activation. More details on the front-to-end simulations will be available in [6].

Table 2: Results of the Tracking Simulations Including Beam-beam and Synchrotron Radiation for Several ERL Designs

ERL size	**1/3 C_{LHC}**	**1/4 C_{LHC}**	**1/5 C_{LHC}**
$\gamma\,\varepsilon_x^{inj}$ [μm rad]	25.4	22.7	15.1
$\Delta p/p$ at IP	0.021 %	0.029 %	0.041 %
transmission	99.93 %	98.89 %	98.40 %
energy recovery	97.9 %	96.7 %	95.4 %

CONCLUSION

The front-to-end tracking simulations show great energy recovery performances that decrease with the ERL circumference. It demonstrates that the ERL, as it is designed and optimised, also including the synchrotron radiation and the beam-beam disruption provides an excellent transmission of close to 100%. The simulations constitute a foundation for future LHeC studies like magnet errors and alignment tolerances.

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