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STUDIES OF THE ENERGY RECOVERY PERFORMANCE OF THE PERLE PROJECT*

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Abstract

The Powerful Energy Recovery Linac for Experiments (PERLE) is an accelerator facility for the development and application of the energy recovery technique for an intense 500 MeV electron beam. The paper presents the studies that have been performed to assess the quality of the ERL lattice design and beam optics. The studies include the Coherent Synchrotron Radiation (CSR) emission and wakefields in the superconducting radio-frequency structures of the linacs. The lattice design and optics principles of the ERL structure are discussed, involving the vertical deflection system and the 180° arcs. Finally, the results of the front-to-end tracking simulations that consider the complete multi-turn energy recovery process are presented.

INTRODUCTION

The PERLE ERL considers a multi-turn energy recovery linac for the production of a high power electron beam proposed to two experimental areas with low beta insertions at 500 MeV. PERLE will be the development hub for the multi turn energy recovery technology, with a CW operation mode in the 10 MW power range. A particular challenge will be that the SRF cavities have to sustain a very high beam current that excites High Order Modes (HOM) and may lead to instabilities. In addition, despite the limited beam energy, CSR effects on the beam quality may be sizeable caused by the high bunch charge. The combination of these effects is studied, with special attention during the deceleration turns where the energy spread increases rapidly as the energy drops.

DESIGN PARAMETERS

A summary of the design parameters is presented in Table 1. The beam parameters have been chosen to match those of the Large Hadron Electron Collider (LHeC) [1] such that it can act as a test bed for the ERL design and SRF technology development. The bunch spacing in the ERL is assumed to be 25 ns, however empty bunches might be required in the ERL for ion clearing gaps.

Table 1: PERLE Beam Parameters

Parameter	Unit	Value
Injection beam energy	MeV	7
Electron beam energy	MeV	500
Norm. emittance $\gamma \varepsilon_{x,y}$	mm mrad	6
Average beam current	mA	20
Bunch charge	pC	500
Bunch length	mm	3
Bunch spacing	ns	24.95
RF frequency	MHz	801.58
Duty factor		CW

ERL LAYOUT

The two linacs are composed of one Superconducting Proton Linac (SPL) [2] style cryomodule with four 5-cell 802 MHz RF cavities. The linac optics design minimises the effect of the wakefields such that the beta function must be minimised at low energy. The ERL is operated on-crest in order to benefit from the maximum voltage available in the cavity. A schematic of the ERL geometry is shown in Fig. 1.

The spreaders/recombiners connect the linac structures to the arcs and route the electron bunches according to their energies. The design is a two-step achromatic vertical deflection system and features a specific magnet design in order to gain in compactness.

The three arcs on either side of the linacs are vertically stacked and composed of 6 dipoles instead of 4 dipoles with respect to the previous design [3]. The increased number of dipoles allow to reduce the effects of CSR [4]. Moreover the arc lattice is based on a flexible momentum compaction optics such that the momentum compaction factor can be minimised but also adjusted if needed. The low energy implies that the energy spread and emittance growth due to incoherent synchrotron radiation is negligible in the arcs.

The ERL is composed of a pair of low-beta insertions at 500 MeV for experimental purposes. The optimal bunch recombination pattern gives some constraints on the length of the arcs. Furthermore, the arc with the low-beta insertions will provide the necessary shift to the decelerating phase in the RF cavities.

There are two chicanes in the lattice, located at the entrance of a linac and symmetrically at the exit of the other linac structure. They are needed to allow the injection and extraction through a constant field. The injection in the ERL takes place at 7 MeV with an angle of around 20°, a precise description of the injector beam line can be found in [5].

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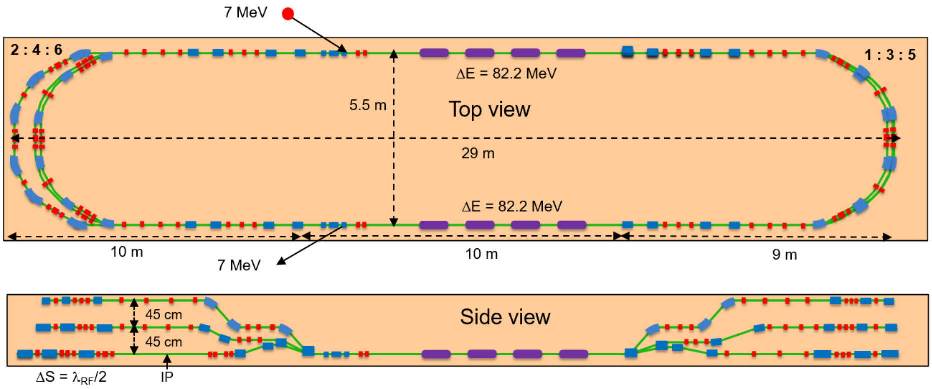

Figure 1: Top and side views of the PERLE energy recovery linac.

TRACKING OF THE ERL

The tracking of the ERL has been studied with PLACET2 tracking code [6] and features the Coherent Synchrotron Radiation (CSR) and the long range wakefields interaction between bunches separated by 25 ns. The CSR studies will show the impact of high bunch charge on the beam dump phase space, and on the transmission. The effects of the High Order Modes (HOM) in the RF cavities will be addressed in order to assess the multi bunch multi turn ERL operational stability.

The optics design of the multi turn ERL is shown Fig. 2 and present the sequence of linacs and arcs leading to the two interaction regions where experiment setups will be placed. One observes the relatively low values of the beta function along the ERL since the beam emittance is in fact larger at low energy.

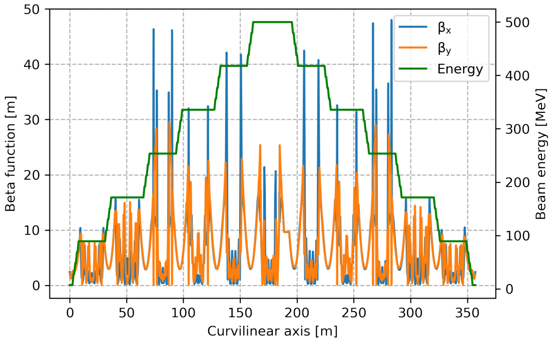

Figure 2: Plot of the beta functions and the beam energy along the multi-turn ERL operation.

The plain tracking of the initial 3 mm rms bunch length shows that it is difficult to have a non distorted longitudinal phase due to the RF curvature that elongates the bunch even with the optimised flexible momentum optics provided by the arcs. The bunch is longitudinally bent during the accelerating phases following the cosine shape of the voltage in the RF cavities therefore having particles with less energy on either sides of the core. However during the deceleration passages the RF curvature changes and the bunch is distorted in the opposite direction shown in Fig. 3.

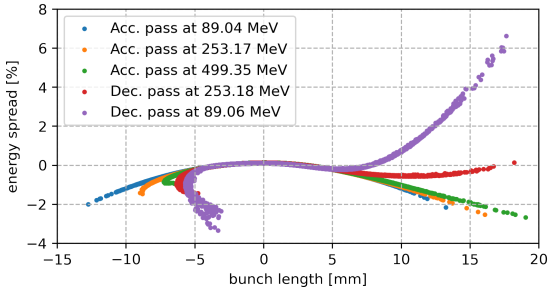

Figure 3: Longitudinal phase space distribution at the exit of the linac for several stages of the ERL operation with a bunch length $\sigma_s = 3$ mm.

Therefore the electron bunch length will need to be reduced but this might create an issue with the CSR and microbunching may appear. A bunch length of 1.4 mm has been tracked since it lies in between the LHeC bunch length of 600 µm and the 3 mm proposed for PERLE. The plain tracking results are shown in Fig. 4 and present the effect of the RF curvature along the ERL operation.

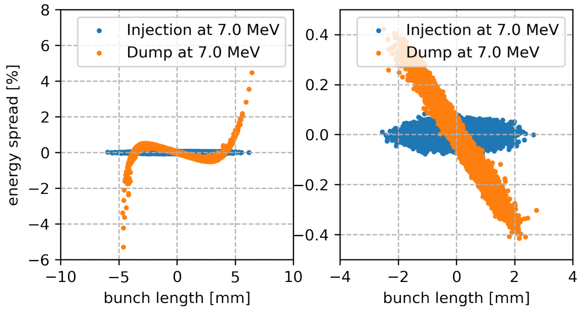

Figure 4: Longitudinal phase space distribution comparison between a bunch length of 1.4 mm (left) and 0.6 mm(right).

The influence of the RF curvature reduces with decreasing bunch length, which is a potential solution to deal with the non linearity of the on-crest operation of the ERL. Nevertheless, shorter bunches will be more vulnerable to the detrimental impact of CSR.

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Coherent Synchrotron Radiation in the ERL

There is a negligible effect of the incoherent synchrotron radiation due to the low energy of the beam. However due to the large bunch intensity, the coherent synchrotron radiation distorts the beam longitudinally and it ultimately affects the transverse plane leading to potential losses. The long bunches are less affected by CSR, but do experience the non linearity of the RF field.

Therefore, an intermediate bunch length was studied in order to observe the effect of an increase of the beam current. The impact of CSR is shown in Fig. 5. The RF curvature having a known influence on the distortion of the longitudinal phase space one can see the additional effect of CSR. In fact, a beam current of 2 mA does slightly modify the longitudinal phase space tracking whereas a micro-bunching phenomenum occurs for 20 mA.

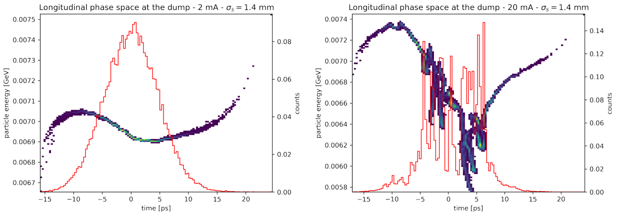

Figure 5: Longitudinal phase space at the dump including CSR for different beam current. The histogram in red represents the longitudinal distribution. Left: Results with 2 mA. Right: Results with 20 mA.

The plain tracking results give a perfect transmission for a bunch length of 0.6 mm and 1.4 mm. However a transmission of 99.5% is observed for 3.0 mm bunch length due to the large distortion created by the RF curvature as the beam is accelerated on-crest. Furthermore CSR shows an increasing impact on the longitudinal phase space as the bunch charge increases. The micro-bunching that appears at a beam current close to 20 mA does not lead to losses for a bunch length of 1.4 mm.

Long Range Wakefields

After a successful lossless single bunch tracking including CSR, the multi bunch tracking has been studied with the addition of the long range wakefield interaction between bunches. The HOM are the ones of the SPL cavity scaled to 801.58 MHz and with a unique quality factor of 10^5 for all the modes, that is the highest quality factor among the modes of the SPL cavity. The studies combined the CSR and the long range wakefields interactions in order to look at the amplitude of the 52 horizontal and vertical modes for each bunch passage in the RF cavities. The objective was to track if at least one of the modes had an increasing amplitude that could lead to instabilities.

The tracking results show that two modes build up with a bunch charge of 500 pC or 20 mA beam current, see Fig. 6. However the addition of a frequency detuning of 10^{-3} of the HOM in the cavities can remove the development of these specific modes for the same bunch charge. Figure 7 shows the results of the amplitude of each of the modes along the bunch passage in the RF cavities. The frequency detuning of the cavity does seem to contribute to the mitigation of the build up of HOM in the RF cavities and therefore guarantees the stability during the ERL operation.

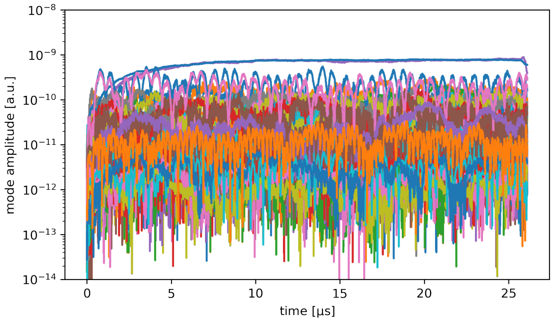

Figure 6: Study of the HOM amplitudes within the RF cavities. A new electron bunch is injected every 25 ns.

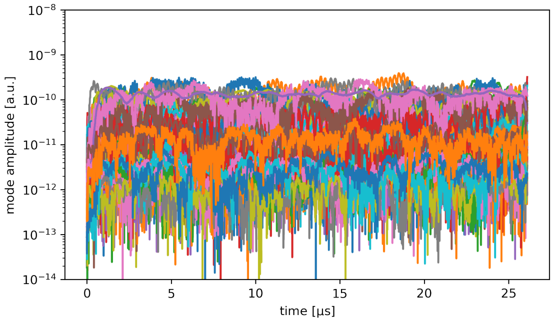

Figure 7: Study of the HOM amplitudes within the RF cavities including detuning. A new electron bunch is injected every 25 ns.

The multi bunch tracking results showed the growth of some transverse modes that can disappear by decreasing the beam current or by considering a frequency detuning of the HOM. The multi bunch tracking showed a build up of two modes that disappear for a frequency detuning of 10^{-3}. Further studies will refine the influence of the frequency detuning and address the effect of the bunch recombination pattern within the linac since there is evidence that the most disturbed bunches heading to the dump must be as far as possible from the newly injected bunches.

CONCLUSION

The ERL lattice design provides a pair of low-beta insertions for experimental purposes and the multi-pass optics optimisation give a perfect transmission with the front-to-end tracking results including CSR. Multi bunch tracking has shown that instabilities from HOM can be damped with frequency detuning.

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