STRAWMAN OPTICS DESIGN FOR THE LHeC ERL TEST FACILITY

A. Valloni[*], O. Bruning, R. Calaga, E. Jensen, M. Klein, R.Tomas, F. Zimmermann,
CERN, Geneva, Switzerland
A. Bogacz, D. Douglas, Jefferson Lab, Newport News Virginia

Abstract

In preparation for a future Large Hadron electron Collider (LHeC) at CERN, an ERL test facility is foreseen as a test bed for SRF development, cryogenics, and advanced beam instrumentation, as well as for studies of ERL-specific beam dynamics. The CERN ERL test facility would comprise two linacs, each ultimately consisting of 4 superconducting 5-cell cavities at ∼802 MHz, and two return arcs on either side; a final electron energy of about 300 MeV is reached. The average beam current should be above 6 mA to explore the parameter range of the future LHeC. In this paper we present a preliminary optics layout.

INTRODUCTION

The LHeC is a proposed new machine at CERN which will collide the 7-TeV protons circulating in the Large Hadron Collider (LHC) with a high-energy lepton beam at a single collision point [1]. The LHeC ERL approach allows a comparable or even higher machine performance as compared to the LHeC Ring-Ring option. The multitude of ERL projects and proposals worldwide attests to the powerful benefits of this technology. The ERL scheme, as an alternative accelerator concept for accelerating efficiently intense beams, intends to accomplish the operational efficiency of a storage ring while maintaining the superior beam quality typical of a linear accelerator. The proposed machine layout, described elsewhere [1], consists of a 500 MeV polarized injector, two CW 10 GeV superconducting linacs and a recirculator system. Each beam recirculates up to three times through both linacs to boost the energy to 60 GeV. After the beam is focused and collided it is phase shifted by 180° and then sent back through the recirculating linac at a decelerating RF phase. During deceleration the energy stored in the beam is reconverted to RF energy and the final beam, at its original energy, is directed to a beam dump. The baseline 60 GeV ERL option of the LHeC can generate an ep luminosity in excess of $10^{33}\text{cm}^{-2}\text{s}^{-1}$, at a beam-current of 6.4 mA, with less than 100 MW total electrical power required. First activities for the development and feasibility demonstration of the final LHeC machine focus around the conception of an ERL test facility.

This ERL test facility foreseen at CERN, aims at a 100-MeV scale energy recovery demonstration of a recirculating superconducting linear accelerator. The test facility should serve as a test bed to gain quantitative and qualitative understanding of the electron beam recovery process. The purposes of this test facility are first, confirming the feasibility of the LHeC ERL design by demonstrating stable intense electron beams with the intended parameters (current, bunch spacing, bunch length); secondly, testing novel components such as a (polarized) DC electron gun, superconducting RF cavities, cryomodule design and feedback diagnostics; finally, experimental studies of the lattice dependence of stability criteria. The realization of this facility will allow addressing several physics challenges such as maintaining high beam brightness through preservation of the six dimensional emittance, managing the phase space during acceleration and energy recovery, stable acceleration and deceleration of high current beams in CW mode operation. The facility design must also allow addressing other performance aspects such as longitudinal phase space manipulations, effects of coherent synchrotron radiation (CSR) and longitudinal space charge, halo and beam loss and microbunching instability. These issues could have sizeable impacts on machine performance in the region of the design parameter space. Thus a picture emerges of a system that, in principle, needs to be flexible in supporting multiple operating points and indeed, provides a reasonable validation of the LHeC project. With regard to the demand of versatility the system design is moving forward with respect to the scheme developed previously and discussed in [2]. The ERL necessitates diagnostics requirements beyond those normally present in linacs and storage rings; an appropriate diagnostic apparatus must be intrinsic to the system design in order to build up confidence with the most severe limitations and hurdles to ERL performance. Planned diagnostic equipment to characterize the beam transport includes beam position monitors, optical-transition-radiation-based beam viewers, beam-current monitors, scrapers/halo detectors, phase monitors, energy spread and emittance measurements devices, monitors for beam breakup (BBU) studies and energy feedback systems.

In the following we discuss preliminary system specifications and design studies addressing the impact of requirements on the machine architecture, including input from the recent LHeC meeting held in Daresbury Laboratory [3]. We report latest improvements, future ideas and plans, focusing on some details of the machine optics. Several possible scenarios of ERL beam optics are presented and two possible machine outlines are displayed.

SYSTEM ARCHITECTURE

A demanding effort is required to develop and evaluate a baseline design of the ERL configuration. Our project

---

[*] alessandra.valloni@cern.ch

consists of the following elements:

1. a 5 MeV in-line injector with an injection chicane;
2. superconducting linacs consisting of two (or one) cryomodules of in total eight 5-cell SC structures;
3. optics transport lines including spreader regions at the exit of each linac to separate and direct the beams via vertical bending, and recombiner sections to merge the beams and to match them for acceleration through the next linac;
4. beam dump at 5 MeV.

A two-pass recirculating linear accelerator will enable operation in the energy recovery mode. Flexibility in the design will eventually permit to support additional passes to increase the final beam energy. The prototype architecture will produce 300 MeV beams with a target current of about ∼6 mA. Different candidate RF frequencies for the SC linac have been examined, and the final choice of ∼802 MHz, is mainly dictated by a comprise of cost considerations and beam dynamics issues (e.g. beam loading effects and transverse wake fields), along with functional synergies with other existing systems. Considerable further details concerning the RF aspects as well as an alternative baseline design are included in a companion paper [4]. The set of main parameters incorporated into the ERL prototype injector is shown in Table 1. A comprehensive layout of the accelerator complex is rendered in Fig. 1. The beam is injected into the linac at 5 MeV and accelerated to ∼152 MeV by one full cryomodule. Next, the beam is recirculated and sent through the linac for a second pass where it is accelerated to 300 MeV; the recirculator is configured for energy recovery in which the beam is decelerated back to 5 MeV. This scheme, as a first stage, could provide features to explore beam dynamics performance more generally. Use of separated transport lines along the whole system, except for the single linac, facilitates management of the 6-D beam phase space throughout the machine, a complete understanding of the limitation to the average current imposed by BBU, and optimization of transport system aberrations by means of the choice of betatron match and phase advance. Moreover, this configuration, accommodates for available space on the straight section opposite to the linac for implementation of feed-back, phase-space manipulations, and beam diagnostic instrumentation, giving the possibility of a full validation testing. A subsequent upgrade could be the installation of an additional cryomodule to raise the beam energy up to 600 MeV. A conceptual layout of such a scheme including two linac modules, is shown in Fig. 2. The facility, in this new configuration, could represent, in principle, a smaller clone of the final LHeC project and could, undoubtedly, be adopted as a pre-accelerator/injector to the final 60 GeV machine.

Table 1: Relevant Beam Parameters for the Injector.

Parameter	Value
Energy	5 MeV
Beam Charge	>300 pC
Bunch length (rms)	<3 mm
Energy spread (rms)	<10 keV
Normalized transverse emittance (rms)	<25 mm-mrad

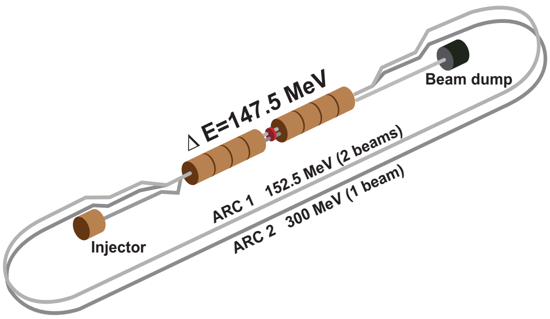

Figure 1: ERL test facility providing increased operational flexibility. Arc 1, at 152 MeV, is shared by the accelerating and decelerating beam.

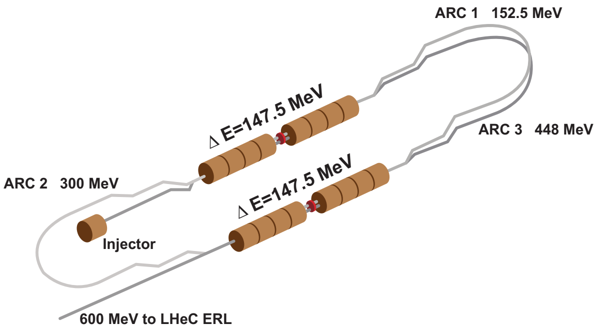

Figure 2: Subsequent upgrade to LHeC pre-accelerator. By modifying the machine backleg to include a second full cryomodule, the recirculator can deliver a higher beam energy of 600 MeV.

TRANSPORT OPTICS

Appropriate recirculation optics are of fundamental concern in a multi-pass machine to preserve beam quality. The design comprises three different regions, the linac optics, the recirculation optics and the merger optics. The focusing strength of the quadrupoles along the linac needs to be set to transport two co-propagating beams of different energy and to support a large number of passes. Referring to Fig.1 at the end of the linac the beams need to be directed into the appropriate energy dependent arc. Disturbing effects on the beam phase-space such as cumulative emittance and momentum growth have to be counteracted through a pertinent choice of the basic optics cell. A class of Flexible Momentum Compaction (FMC) cells has been planned to be installed in the LHeC machine. This choice, due to the need of controlling emittance increase, momentum spread growth and isochronicity, resulted in a quasi isochronous arc for the two lowest energy paths (beta-functions are kept small in order to limit the required vacuum chamber size and consequently the magnet aperture), FMC double bend achromat-like (DBA) cells for the intermediate arcs, and FMC theoretical emittance minimum-like (TEM) cells for the highest energy arcs to keep the emittance growth from synchrotron radiation limited [5]. With regard to the optics option for the test facility, operational flexibility motivates the final choice. The intention is to come up with a system design that gives an independent handle on as many different parameters as possible, without adversely influencing others. This essentially leads to the question of how to manage/control momentum compaction, as it is a significant beam dynamics issue related to the arc optics. For beams with non-zero energy spread, one would like to employ a quasi-isochronous arc to limit bunch lengthening in the subsequent linac and the synchronous condition can by defined in terms of a tolerable RF phase delay for a given momentum acceptance. Diverse plausible optics layouts are taken into consideration. We are primarily comparing performances of FMC cells and FODO based cells. In our analysis we try to keep track of controls on dispersion, momentum compaction, phase advance, chromatic aberrations and nonlinear phase space management. Concerning lattice chromaticity, several measures including second order dispersion and chromatic amplitudes are being computed for three different cell types, an FMC cell, a 6-cell FODO lattice (with 60° horizontal phase advance and 90° vertical phase advance per cell) perturbed by a closed dispersion bump (excited at the third and the ninth quadrupoles) to control the transport matrix element M_{56}, and a more compact FODO arc also based on 90°/60° horizontal/vertical phase advance per cell. To obtain a wide momentum aperture of the recirculating loop, as well as to preserve low projected emittances, the chromaticity corrections have to be examined carefully. Due to the demand of providing a reasonable validation of the LHeC final system our plan is, at present, more oriented towards employing a FMC cell based lattice. Specifications require isochronicity, path length controllability, large energy acceptance, small higher-order aberrations and tunability. An example layout which fulfills these conditions is shown in Fig. 3. The result presented describes a possible optics scheme for the lower energy arc of Fig. 1 and it includes a two-step-achromat spreader and a mirror symmetric recombiner to separate the low-energy arc from the one at a higher energy. The vertical dispersion introduced by the first step bend is suppressed by two quadrupoles located appropriately between the two stages. The design necessitates two families of sextupoles to compensate second-order aberrations. A next step will be the study of a hardware solution which could work at the same time as an FMC cell and as a FODO based second order achromat cell.

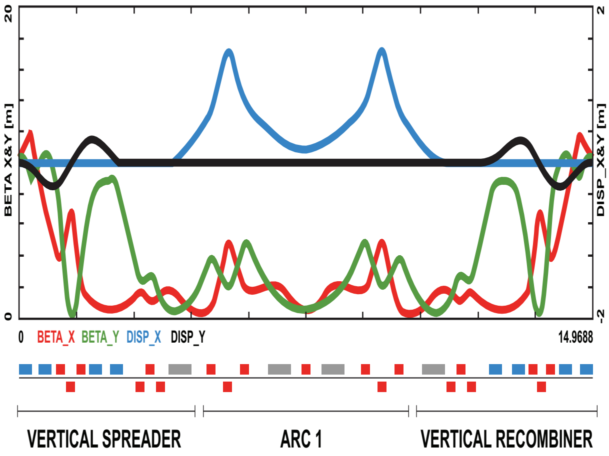

Figure 3: Optics based on an FMC cell of the lowest energy return arc at 152 MeV. Horizontal (red curve) and vertical (green curve) beta-functions amplitude are illustrated. Blue and black curves show, respectively, the evolution of the horizontal and vertical dispersion.

CONCLUSIONS

An ERL based collider in which a newly provided electron beam collides with the intense hadron beams of the LHC represents a major opportunity for progress in particle physics. A proposal for a scientific and technical R&D facility preparing to LHeC is now under active development. Here we have described the CERN ERL test facility purposes and specific requirements along with two conceivable layout schematics. The ultimate goal is a design that operates on a multiple operating points in order to allow for a comprehensive validation testing of the key concepts for the final LHeC.

ACKNOWLEDGMENT

Helpful discussion and valuable input from all members of LHeC Study Group Collaboration are thankfully acknowledged. This work is supported by the European Commission within the oPAC project under Grant Agreement 289485.

REFERENCES

[1] J. L. Abelleira Fernandez, *et al.* [LHeC Study Group Collaboration], J. Phys. G **39** (2012) 075001 [arXiv:1206.2913 [physics.acc-ph]].

[2] R. Calaga, E. Ciapala and E. Jensen, *Proposal for an LHeC ERL Test Facility at CERN*, CERN-LHeC-Note-2012-006 ACC.

[3] LHeC Collaboration, *LHeC Meeting*, Daresbury Laboratory, January 2013, https://eventbooking.stfc.ac.uk/news-events/lhec-meeting.

[4] R. Calaga, *et al.*, *A proposal for an ERL test facility at CERN*, these proceedings.

[5] S.A. Bogacz, I. Shin, D. Schulte, F. Zimmermann, *LHeC ERL Design and Beam-dynamics Issues*, in Proceedings of the 2011 International Particle Accelerator Conference, San Sebastin, Spain.