LHeC ERL DESIGN AND BEAM-DYNAMICS ISSUES*

S.A. Bogacz#, I. Shin, Jefferson Lab, Newport News, VA, USA
D. Schulte, F. Zimmermann, CERN, Geneva, Switzerland

Abstract

We discuss machine and beam parameter choices for a Linac-Ring option of the Large Hadron electron Collider (LHeC) based on the LHC [1]. With the total wall-plug power limited to 100 MW and a target current of about 6 mA the desired luminosity of 10^{33} $cm^{-2}s^{-1}$ can be reached, providing one exploits unique features of the Energy Recovery Linac (ERL). We describe the overall layout of such ERL complex located on the LHC site. Multi-pass linac optics enabling operation of the proposed 3-pass Recirculating Linear Accelerator (RLA) in the Energy Recovery mode is presented. We also describe emittance preserving return arc optics architecture; including layout and optics of the arc switchyard. Furthermore, we discuss importance of collective effects such as multi-pass beam breakup instability (BBU) in ERL.

INTRODUCTION

An ERL is a powerful alternative accelerator concept which combines characteristics of both storage rings and linacs, and is potentially capable of accelerating tens of milliamperes of average current to several tens of GeV. In contrast to storage rings, which store the same electrons for hours, ERLs store the energy of the electrons instead. Because the time individual electrons spend in an ERL is short compared to a typical radiative emittance build-up time, equilibrium is never established. A typical ERL consists of an injector, a linac, or a pair of linacs, recirculating arcs and a beam dump. The principle of energy recovery is to both accelerate and decelerate the same beam in the same RF linac, by a proper choice of the time-of-arrival of the electron bunches on successive passes. As a result of energy recovery, the RF power required for acceleration becomes nearly independent of the beam current.

ERL RECIRCULATOR COMPLEX

The proposed Recirculator RLA complex consists of the following components:

- 0.5 GeV injector with a injection chicane
- A pair of 720 MHz SCRF linacs, each linac one kilometer long with energy gain 10 GeV per pass
- Six 180˚ arcs, each arc 1 km radius
- Extraction dump at 0.5 GeV

The overall layout of the ERL accelerator complex is illustrated schematically in Fig. 1.

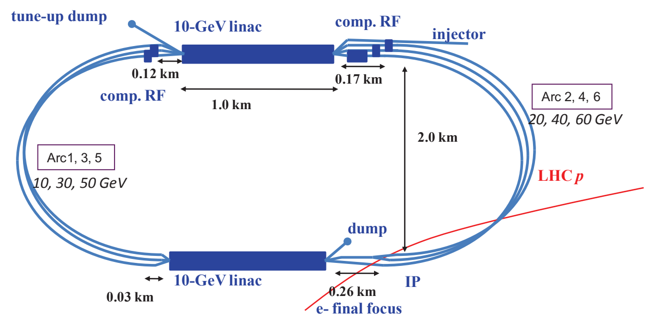

Figure 1: Schematic layout of a 3-pass up/3-pass down ERL.

Multi-Pass Linac Optics

The key element of the transverse beam dynamics in a multi-pass RLA is an appropriate choice of the multi-pass linac optics. The focusing profile along the linac (i.e. the constant quadrupole gradients) need to be set so that one can transport (and provide adequate transverse focusing for a given aperture) multiple pass beams over a vast energy range. Naturally, one would like to optimize the focusing profile so as to accommodate a large number of passes through the RLA. In addition, the requirement of Energy Recovery puts a constraint on the exit/entrance Twiss functions for the two linacs. We will examine a strongly focusing linac optics based on a 130˚ FODO lattice as a starting point to design the multi-pass linac optics for the Recirculator. Each 130˚ FODO cell contains four groups of 8 RF cavities. The entire 1 km linac is built from 18 such cells. For the lowest energy pass the focusing profile for the linac was chosen to maintain a constant betatron phase advance per cell of 130˚ along the entire linac. This requires scaling up of the quadrupole field gradients with energy (to assure constant value of *k*). A concise representation of multi-pass ERL linac optics for all six passes, with constraints imposed on the Twiss functions by 'sharing' the same return arcs for the accelerating and decelerating passes is presented in Fig. 2.

Arc Optics – Emittance Preservation

At the ends of each linac the beams need to be directed into the appropriate energy-dependent arcs for recirculation. For practical reasons vertical rather than horizontal beam separation was chosen.

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bogacz@jlab.org

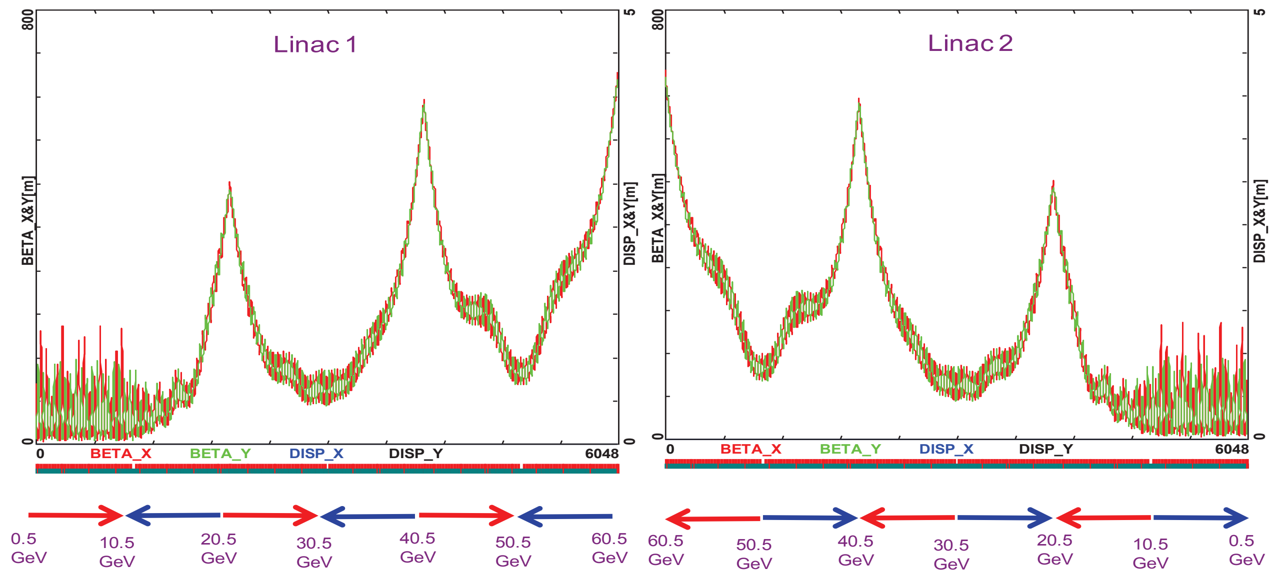

Figure 2: Multi-pass linac optics optimized for 3-pass ERL As a virtue of ER, Linac 1 and 2 are mirror reflections.

Similar to CEBAF, two-step-achromat spreaders and mirror symmetric recombiners have been implemented. The switchyard that separates all three arcs into a 1-meter high vertical stack is illustrated in Fig. 3. The vertical dispersion created by the first step (a pair of opposing vertical bends) is suppressed by two quadrupoles located appropriately between the two steps, which makes a very compact switchyard system (~20 meter long) based on an achromatic spreader optics illustrated in Fig. 3, below.

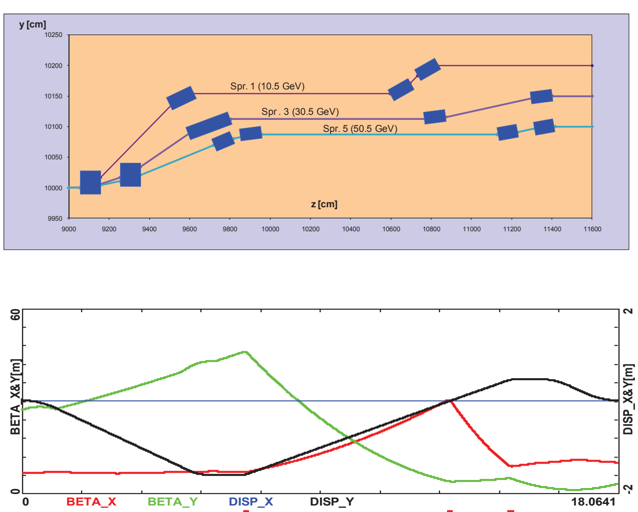

Figure 3: Switchyard layout and spreader optics.

The initial choice of a large arc radius (1 km) was chosen in order to limit the energy loss due to synchrotron radiation at top energy (~60 GeV) to less than 1%. However other adverse effects of synchrotron radiation on the electron beam phase-space, such as cumulative emittance and momentum growth due to quantum excitations, are of paramount importance for a high luminosity collider that requires a normalized emittance of 50 mm mrad. One can characterize the phase-space dilution in terms of the normalized emittance increase expressed by the following formula [2]:

$$\Delta\varepsilon^N = \frac{2}{3} C_q \, r_0 \, \gamma^6 \left\langle H \right\rangle \frac{\pi}{\rho^2} \tag{1}$$

$$H = \gamma D^2 + 2\alpha D D' + \beta D'^2$$

where <H> is the dispersion invariant (a purely lattice dependent quantity) averaged over the bends.

Here, we will explore a class of Flexible Momentum Compaction (FMC) cells to optimize both the emittance preservation and the isochronicity (small momentum compaction, M_{56}). By replacing one of the singlets in the FODO cell by a triplet one can then tune this cell to various flavours of FMC optics by appropriately tailoring the values of <H> and M_{56}, as required by emittance dilution and isochronicity specifications for arcs of different energy as illustrated in Fig. 4.

Now, one can establish the emittance dilution budget. The highest energy arc (before the final collision), Arc 5 at ~50 GeV, according to Eq. (1) gives a net emittance increase of 4.5 mm mrad. All the lower arcs, even with less emittance preserving optics, shown in Figure 4, contribute a total of about 25% of the value for Arc 5., and the total emittance dilution becomes 5.6 mm mrad. Assuming the initial injection emittance of 44 mm mrad our arc-by-arc optimized FMC Optics allows us to deliver beam with an emittance not exceeding the LHeC design value of 50 mm mrad. After the collision in Arc 6 at ~60 GeV, the beam suffers a net emittance increase of 13.3 mm mrad, which is still small compared to the (unmatched) emittance disruption due to the collision (~180 mm mrad).

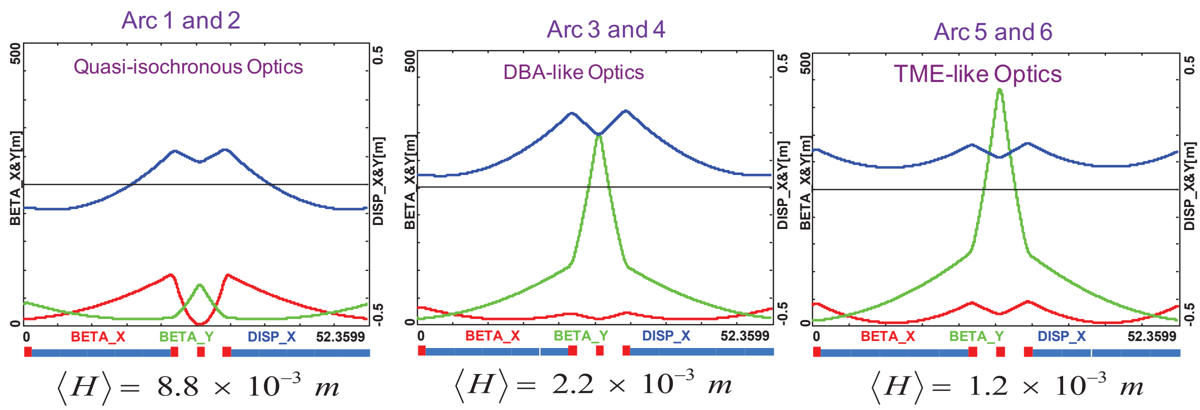

Figure 4: Various flavours of FMC Optics used for different energy arcs with appropriate values of <*H*>.

MULTI-PASS BBU

To gain confidence that an electron current of 6.5 mA, required for the LHeC luminosity is feasible, one needs to investigate multi-pass beam breakup stability for our ERL design. We will summarize results of a recent numerical study using TDBBU code [3] of 6-pass (3 passes 'up' and 3 passes 'down') BBU due to the transverse higher order modes (HOMs) excited in the RF cavities. The beam travelling along each linac experiences cumulative transverse deflection from each cavity HOMs. One needs to study transverse dynamics of the beam interacting with cavity HOMs for the entire passage through the ERL using a specific linac optics for each of six passes, as well as linear transfer maps for the 6 return arcs. In case of the BBU instability the transverse particle positions would increase exponentially and finally the particles would hit a beam pipe.

TDBBU Simulation and Results

The 703.79MHz BNL3 5-cell SRF cavity data serves as a close reference for the HOMs [4]. For our BBU simulation, we consider the highest values of $Q_l = 1\times10^6$ (high-end of the error bar). Out of all HOMs measured [4], we selected 3 most offending HOMs: with the highest R/Q and Q_l values. They are summarized in the table below.

Frequency [MHz]	Q_l	R/Q[Ohm]
1003	1×10^6	32
1337	1×10^6	32
1820	1×10^6	32

For each cavity along the linac, the three HOM frequencies, are randomly distributed with a full width of 2 MHz. Twenty samples for different HOM frequency distributions are generated.

The plots in Fig. 5 show the beam behavior near the threshold. The horizontal axis corresponds to a bunch number and can be considered as an axis of time (if the bunch numbers are divided by frequencies). The vertical axis represents the transverse beam position at the end of the second linac. One can clearly see from Fig. 5, that at 5 mA the transverse beam position is increasing slightly, which indicates the onset of the instability. Finally, at 6 mA one explicitly observes an exponential increase in transverse beam position – a vivid case of beam instability. Therefore, we could infer that the BBU threshold current is somewhere around 5 mA. Our study assumed the 'worst case' interpretation of HOM's measurement for a cavity with limited HOM suppression of only one pair 120° HOM dampers per cavity. This suggests more extended HOM damping will bring the stability threshold above 6.5 mA.

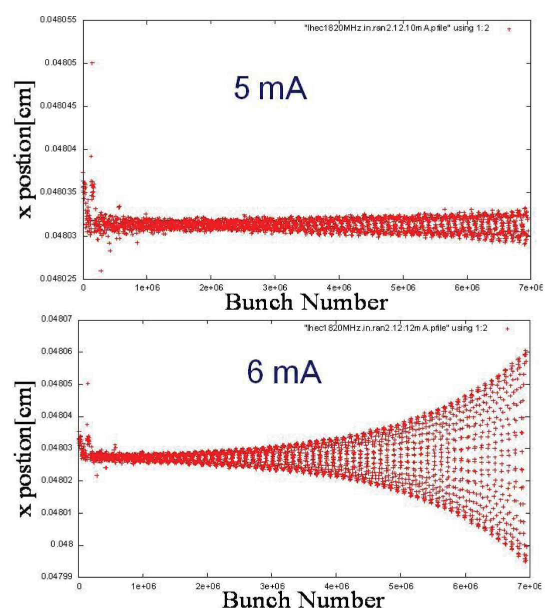

Figure 5: Large scale TDBBU simulation results.

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