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FREE ELECTRON LASER DRIVEN BY A HIGH-ENERGY HIGH-CURRENT ENERGY-RECOVERY LINAC*

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Abstract

The proposed electron-hadron collider LHeC, based on an energy recovery linac, employs an electron beam of 20 mA current at an energy of tens of GeV. This electron beam could also be used to drive a free electron laser (FEL) operating at sub-Angstrom wavelengths. Here we demonstrate that such FEL would have the potential to provide orders of magnitude higher peak power, peak brilliance and average brilliance, than any other FEL, either existing or proposed.

INTRODUCTION

The high-current ERL of the proposed LHeC [1] could also be used to drive a Free Electron Laser (FEL) [2]. Indeed ERL-based FELs already operated, and operate, successfully in the electron-energy range of 10 to 200 MeV, e.g. at BINP [3], JAEA [4], and JLAB [5]. A superconducting energy-recovery linac with a higher beam energy of 0.5–1.0 GeV was proposed to produce 13.5 nm radiation, at 5 kW average power [6]. Most similar to the LHeC-based FEL would be a possible upgrade of the European XFEL, also based on an ERL-type of operation, with 100% duty factor and an average brightness of 1.64×10^{25} photons/s/mm^2/mrad^2/0.1% bandwidth at 8.5 GeV beam energy [7].

In the LHeC design, a 500 MeV electron bunch from the injector is accelerated over three turns in two 10 GeV SC linacs, so as to reach 60 GeV. Three further revolutions, now with deceleration, reconvert the energy of the beam back to RF energy [1]. The beam emittance and energy spread increase with beam energy due to quantum fluctuations.

For the LHeC configuration, the electron-beam emittance is not critical, since the proton-beam emittance is quite large. On the contrary, in order to reach low wavelengths in FEL operation the beam emittance must be sufficiently small. Because of this requirement, the electron beam energy has been chosen to be 40 GeV for FEL operation rather than 60 GeV, which can be achieved in two revolutions (Fig. 1). The accumulated relative energy spread induced by quantum fluctuations and the normalized emittance due to synchrotron radiation in the LHeC ERL arcs at 40 GeV beam energy is 5×10^{-5} and 0.5 μm, respectively. If necessary or useful, these numbers could be reduced by various optics modifications, e.g., by shortening the length of the arc cells.

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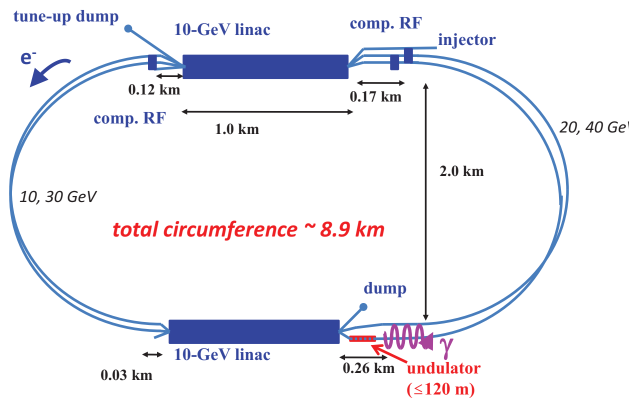

Figure 1: LHeC ERL reconfigured for FEL operation.

BUNCH COMPRESSION

One of the concerns with the LHeC configuration is the need to compress the bunches for FEL operation. Bunch compressors based on chicanes, arcs or wigglers are well established in the case of single-pass systems [8–10]. For example, choosing the proper linac configuration, in the downstream arcs of the SLAC Linear Collider (SLC) the rms bunch length could be compressed by more than an order of magnitude, from more than 1 mm down to about 50 μm [11]. A recirculating linac offers additional degrees of freedom to compress the bunch and also to tailor its longitudinal profile, respectively, e.g. by exploiting the linear momentum compaction in each of the return arcs of the recirculating linac, and by controlling (and cancelling) the second-order momentum compaction through the arc by means of sextupole magnets [12].

We modelled and simulated possible bunch compressor scenarios for the LHeC-based FEL, and found that rms bunch lengths of order 7 μm appear possible [13]. Table 1 presents the electron beam parameters which we have chosen for our LHeC-FEL study. We assume that the bunch is compressed by about a factor of 40 at the location of the undulator, from an initial rms length of 300 μm to an rms length of about 7 μm, as obtained in our simulation. The large bending radius of the LHeC, $\rho \approx 760$ m, combined with a small vacuum chamber, suppresses the emission of synchrotron radiation at long wavelengths and, in particular, the emission of CSR [14,15]. With a reduced pipe diameter of $d \approx 7$ mm at the end of the fourth arc, we would obtain CSR shielding down to $\sigma_{z,\mathrm{sh}} \le 7$ μm, our target bunch length [13].

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Table 1: The Main LHeC-FEL Electron-Beam Parameters

Parameters	Unit	Value
energy	GeV	40.0
electrons per bunch		$3{\times}10^9$
rms bunch length	μm	7
peak beam current	kA	8.2
average beam current	mA	~20
normalized emittance	μm	0.5
bunch spacing	ns	25
rms energy spread	%	0.01

FEL PERFORMANCE

The self-amplified spontaneous emission (SASE) FEL does not require any optical cavity, nor any coherent seed, and it can operate in the X-ray regime. The wavelength of the radiation is given by the well-known formula

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right) \quad (1)$$

where λ_u denotes the period length of a planar undulator, γ the relativistic factor, proportional to the electron energy, and K the undulator parameter [16].

The optimum matching of the electron beam to the light beam is achieved under the condition $\varepsilon \leq \gamma\lambda/(4\pi)$, where ε_N is the normalized emittance. It has been demonstrated that FELs can still operate, albeit with a reduced efficiency, even if the normalized emittance exceeds this optimum condition by a factor of four to five [17]. Consequently, we expect that FEL light of wavelength around 0.5 Å can be produced by 40 GeV electrons with a normalized rms emittance of 0.5 μm. We examine the FEL performance of the LHeC-based FEL for an undulator with a period of 55 mm similar to the soft X-ray undulator of LCLS-II [18].

FEL simulations were performed using the code GENESIS [19] for K values of 4.24, 6.5 and 9.9, corresponding to the wavelengths 0.45 Å, 1 Å and 2.24 Å, respectively. A FODO lattice was selected for its simplicity and cost-effectiveness. The length of each undulator is 3.35 m. Undulator modules are separated by intervals of 66 cm, providing some space for focusing, steering, diagnostics or vacuum-system components. Figure 2 shows the simulation results for the case K=4.24. The saturation occurs after a distance of 110 m and the peak power is approximately 120 GW. We note that, in GENESIS, the coordinate z denotes the longitudinal distance along the undulator, while s measures the position along the radiation pulse. One of the important parameters for comparing different radiation sources is the brilliance. The brilliance describes the light intensity including its spectral purity and opening angle. The brilliance values for two cases are compiled in Table 2, along with some other FEL parameters. Figure 3 compares the LHeC ERL-FEL with a few existing and planned hard X-ray sources [17, 18, 20–22]. Thanks to the high-current high-energy cw electron beam, the average brilliance of the LHeC-FEL is greater by nearly 4 orders of magnitude than for any other FEL source in operation or under construction.

Table 2: LHeC ERL-FEL Radiation Parameters Derived from Simulations. The Peak-Power Values Were Obtained by Averaging the Simulated Power Over the Length of the Pulse ($\pm\sigma_z$). The Unit for the Corrresponding Peak and Average Brilliance (B) is Equal to Photons/mm^2/mrad^2/s/0.1%bw.

Parameters	Unit	K=4.24	6.5
electron energy	GeV	40	40
wavelength	Å	0.45	1
photon energy	keV	27.7	12.41
saturation length	m	110	85
peak power	GW	40	65
pulse duration	fs	60	60
bandwidth	%	0.04	0.05
photons per pulse		$5.2{\times}10^{11}$	$2.5{\times}10^{12}$
peak brilliance	B	$4.5{\times}10^{34}$	$2.6{\times}10^{34}$
average brilliance	B	$1.0{\times}10^{29}$	$6.0{\times}10^{28}$

ENERGY RECOVERY

The high average brilliance is achieved thanks to the high average beam current, which relies on energy recovery. To demonstrate the feasibility of energy recovery during FEL operation, we have simulated the deceleration process from the maximum beam energy about 40 GeV down to about 0.5 GeV, starting with the beam distribution exiting the undulator. This distribution, consisting of 8×10^5 macroparticles and representing a single bunch, was obtained from the GENESIS FEL simulation for the 0.45 Å case. We next used the simulation code PLACET [23, 24] to track the 8×10^5 macroparticles through the exact optics [1, 25] for the last two decelerating turns (four arcs and four linac passages) of the LHeC, composed of 16,000 beam-line elements. To control energy spread and bunch length during deceleration the bunch arrival phase in the linacs was set to $-170°$ instead of the $-180°$ which would correspond to maximum deceleration. The concurrent evolution of transverse emittances and maximum particle position is presented in Fig. 4.

CONCLUSIONS

We have investigated the potential radiation properties of a SASE FEL based on the LHeC Energy Recovery Linac. Our simulations of the FEL process, for a 40 GeV LHeC electron beam passing through an LCLS-II type undulator with 55 mm period, suggest that FEL radiation in the Ångstrom or sub-Ångstrom wavelength regime can be produced, at an exceedingly high peak power and brilliance, far above those of other, existing or proposed X-ray FELs. The high average brilliance relies on the following two features. First, coherent synchrotron radiation is expected to be fully suppressed

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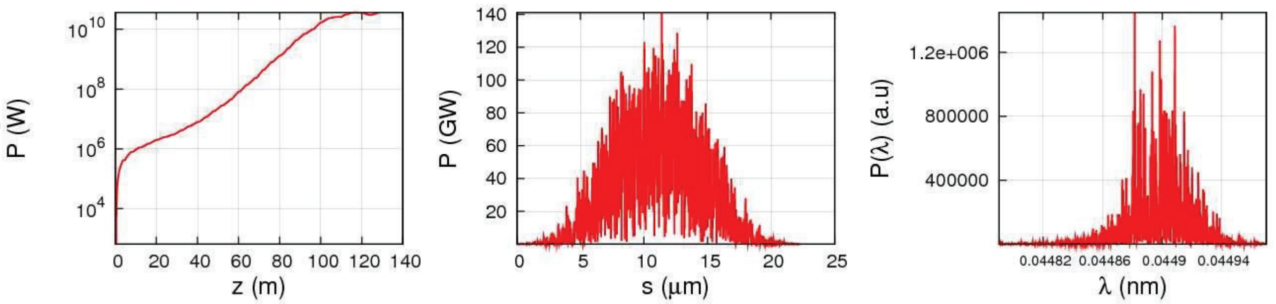

Figure 2: Genesis simulation results for 0.45 Å laser wavelength ($K = 4.24$). Left: Evolution of the pulse power along the undulator. Middle: Spatial profile of the radiation pulse. Right: Wavelength spectrum of the radiation.

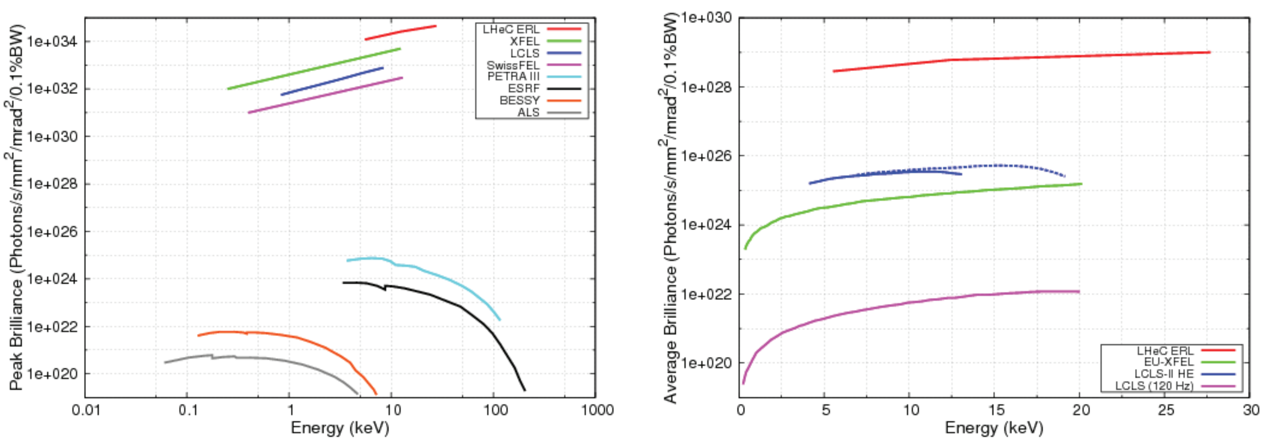

Figure 3: Peak (left) and average brilliance (right) for the LHeC-FEL compared with several existing or planned light sources. The lower curves on the left combine different undulator radiation harmonics. On the right, for LCLS-II-HE the solid curve refers to 8 GeV operation with unmodified injector, while the dashed curve assumes an injector upgrade [26].

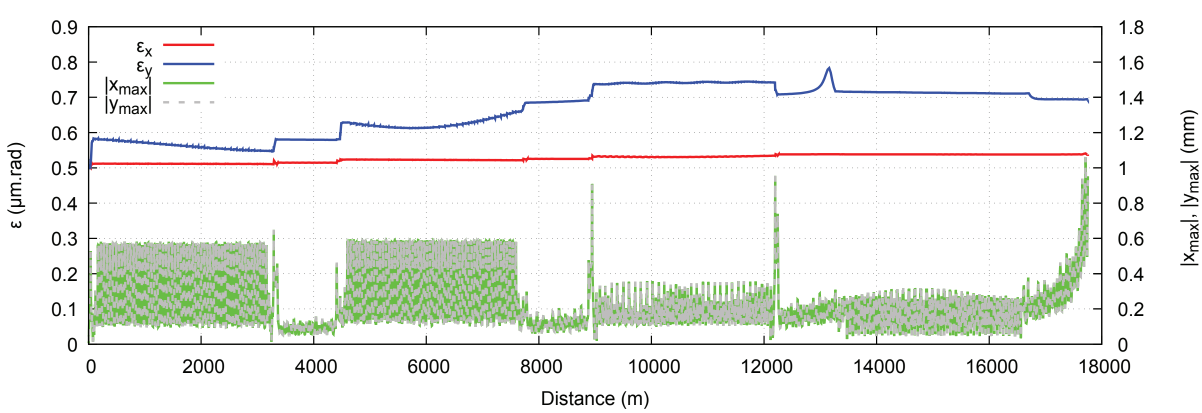

Figure 4: Simulated evolution of the two transverse normalized emittances (after subtracting dispersive contributions) and maximum particle position while decelerating the spent beam over 2 complete LHeC turns from 40 to 0.6 GeV.

by vacuum-chamber shielding, thanks to the large bending radius and small vacuum chamber of the LHeC machine. Second, we have shown that the beam exiting the undulator can be decelerated efficiently from 40 GeV down to 0.5 GeV, without any noticeable beam loss, which is the key prerequisite for the energy recovery mode of FEL operation.

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