LONGITUDINAL PHASE SPACE CONTROL IN THE BERKELEY FEMTOSECOND X-RAY LIGHT SOURCE LUX*

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Abstract

LUX, the proposed Berkeley femtosecond x-ray light source, is a ~2.5 GeV recirculating linear accelerator, where electrons reach their final energy in four passes through a 600 MeV superconducting linac after injection at ~ 120 MeV. An important consideration for this machine is the preservation of the electron beam longitudinal emittance through the various stages of acceleration including injection linac, bunch compression, and various passages through the linac and magnetic arcs. In this paper we analyze the longitudinal dynamics of electrons and define a strategy for the electron beam manipulation leading to a successful conservation of the longitudinal emittance. Particular attention is given to the management of the correlated energy spread induced by collective effects such as longitudinal wake fields and coherent synchrotron radiation (CSR).

INTRODUCTION

Here we report preliminary studies of the longitudinal dynamics of electrons in the recirculating linear accelerator LUX currently under design in Berkeley Laboratory [1]. In this machine the electron bunches are produced in an RF photocathode gun, accelerated in a superconducting injector linac, compressed in the bunch compressor and injected into the recirculating accelerator where they are accelerated to final energy in four passes through the superconducting linac. This scheme possesses rich opportunities for particle manipulation in the longitudinal phase space allowing simple optimization of electron beam parameters at top energy and along the acceleration cycle. One can launch the electron beam at different RF phases on each passage through the linac by adjusting the time that it takes for electron bunch to come back to the linac. This technique can be used to create (or compensate) an energy chirp along the electron bunch with individual features on each orbit turn. It is also possible to regulate the R_{56} time-off-flight parameters of different arcs and control the amount of bunch compression on every orbit turn of the recirculation.

During our study we exercised several different options and chose what we believe is an optimal one. The driving criterion for this choice was obtaining an electron bunch at top energy with small energy spread (less than 1 MeV) and with a pulse duration of 2-3 ps. In all studies significant effort was given to optimization of the injection chain, namely to acceleration in the injector linac, linearization of the electron beam footprint in the longitudinal phase space with a third harmonic cavity, creation of the correlated energy chirp along the electron bunch before bunch compression, and finally to the bunch compression. This system is briefly described in another report at this conference [2]. In this report we focus mainly on the electron beam acceleration in the recirculating accelerator.

RESULTS

Our present scheme assumes acceleration of a ~ 20 ps electron bunch to ~ 120 MeV and its compression to ~ 2.5 ps before injection into the recirculating accelerator. No further compression in the recicrculating accelerator is considered, since we found that it is difficult to deal with CSR effects in the magnetic arcs for a shorter bunch. We also tried gradual compression of the electron bunch in the recirculating accelerator along the acceleration and found it somewhat less attractive than acceleration of a short bunch right after injection. However the optimum is rather shallow as one can judge from Figure 1.

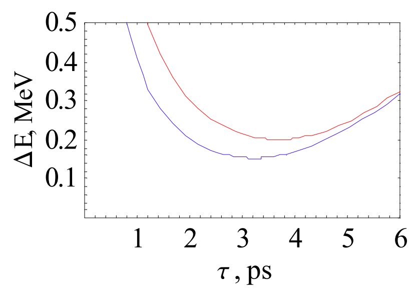

Figure 1. Energy spread at the end of the acceleration versus the bunch length: longitudinal emittance $6\text{x}10^{-7}$ eV-s (red curve) and $4\text{x}10^{-7}$ eV-s (blue curve).

This figure shows beam energy spread at the final energy as a function of the bunch length calculated for two values of the normalized longitudinal emittance: $6\text{x}10^{-7}$ eV-s and $4\text{x}10^{-7}$ eV-s. Since we consider a uniform rectangular distribution these numbers represent an entire phase space area. The emittance contribution dominates when the electron bunch is short while for a longer bunches electrons sample more non-linearity in the acceleration field and this leads to increased correlated energy spread in the bunch. Thus there appears a shallow minimum near 3 ps bunch length. We chose to have a slightly shorter bunch length to provide a better match to the x-ray beam line optics.

We include longitudinal wake field effects in the linac and CSR effects in the arcs in our analysis. In this study we did not consider wake fields related to the resistive wall effects. In order to account for the longitudinal wake field effects in the linac we use the wake function:

$$w(s)\left[\frac{\text{V}}{\text{pC m}}\right] = -38.1\left(1.165\exp\left(-\sqrt{\frac{s}{3.65\,\text{mm}}}\right) - 0.165\right) \quad (1)$$

given in [3] for a point charge steady state wake of a long linac. For a uniform stepped function charge distribution shown in Figure 2 we calculate energy loss of electrons as a function of their position in the bunch using the following expression:

$$\frac{1}{Q}\frac{dE(s)}{dz}\left[\frac{\mathrm{eV}}{\mathrm{pC\,m}}\right] = -19.05\int_{-1}^{2s/l_b}\left(1.165\exp\left(-\sqrt{\frac{s - x(l_b/2)}{3.65\,\mathrm{mm}}}\right) - 0.165\right)dx \qquad (2)$$

where l_b is the bunch length. The right hand side of Eq. (2) can be fitted by a quadratic polynomial with high precision and for 2 ps bunch length we obtain:

$$\frac{1}{Q}\frac{dE(s)}{dz}\left[\frac{\mathrm{eV}}{\mathrm{pC\,m}}\right] = -15.25 - 13.72\left(\frac{2s}{l_b}\right) + 1.33\left(\frac{2s}{l_b}\right)^2 \qquad (3)$$

This formula was used in our calculations. The agreement between formulae (2) and (3) is demonstrated in Figure 3.

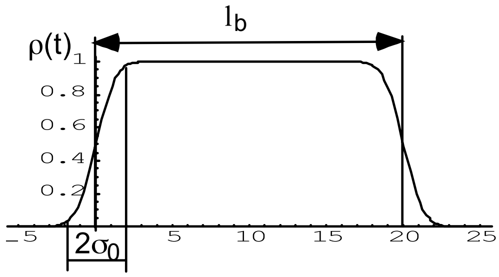

Figure 2. The longitudinal density of electrons.

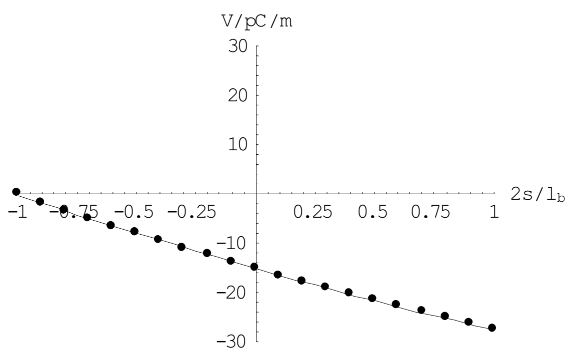

Figure 3. The longitudinal wake function for the linac. Dots show calculations using exact expression (2) and the solid line show calculations using fitting formula (3).

In order to account for CSR effects we used the CSR wake function from [4] and obtained the following energy loss per unit length of trajectory:

$$\frac{dE(s)}{dz} \cong -\frac{2}{3^{1/3}\sqrt{2\pi}}\frac{Ne^2}{\sigma_0\rho^{2/3}}\int_{-\infty}^{s}\left(e^{-\frac{s'^2}{2\sigma_0^2}} - e^{-\frac{(s'-l_b)^2}{2\sigma_0^2}}\right)\frac{ds'}{(s-s')^{1/3}}, \qquad (4)$$

where N is a number of particles per bunch, and e is the electron charge. Deriving (4), we assume a uniform longitudinal density distribution $\lambda(s) = N/l_b$ in interval $0 < s < l_b$ with smooth transitions at the edges with a characteristic length σ_0 as shown in Figure 2.

Integral (4) can be evaluated in analytical functions. Figure 4 shows the plot of $dE(s)/dz$. One can notice that $dE(s)/dz \sim 1/s^{1/3}$ over the entire length of the bunch excluding edges. For this functional dependence one can consider partial compensation of the energy variation within the electron bunch induced by CSR by using off-crest acceleration in the linac.

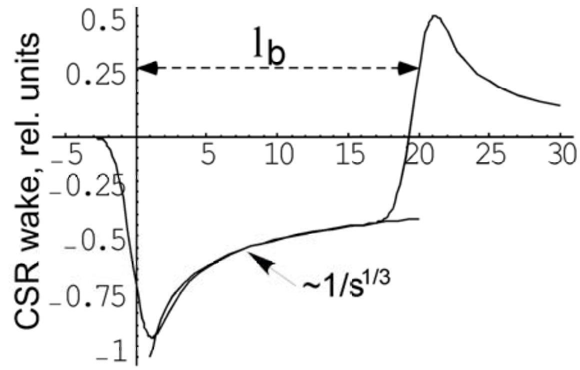

Figure 4. CSR induced energy loss $dE(s)/dz$ for an electron density distribution shown in Fig. 2.

Using $1/s^{1/3}$ dependence for CSR wake function one can calculate the average energy loss per electron due to CSR in the magnet of the length L_m for main core particles with the expression [4]:

$$\Delta E = \frac{L_m}{l_b}\int_0^{l_b}\frac{dE(s)}{dz}ds \cong \frac{3^{2/3}Ne^2}{\rho^{2/3}l_b^{4/3}}L_m. \qquad (5)$$

This is the so-called free space radiation. In practice, the electron bunch moves inside the vacuum chamber that acts as a waveguide for the radiation. Not all spectral components of the CSR propagate in the waveguide and therefore the actual radiated energy is less than in the free space environment. For an estimation of the shielding effect of vacuum chamber we follow recipe suggested in [5]:

$$\Delta E_{\mathrm{shielded}}/\Delta E_{\mathrm{free\,space}} \cong 4.2(n_{th}/n_c)^{5/6}\exp(-2n_{th}/n_c), \quad (n_{th} > n_c) \qquad (6)$$

Here $n_{th} = \sqrt{2/3}(\pi\rho/h)^{3/2}$ is the threshold harmonic number for a propagating radiation, h is the height of the vacuum pipe, $n_c = \rho/c_c$ is the characteristic harmonic number for a Gaussian longitudinal density distribution with the rms value of σ_c. The meaning of n_c is that the spectral component of the radiation with harmonic numbers beyond n_c is incoherent. We define $\sigma_c = l_b/3.22$. This gives us the closest approximation of spectra for the uniform stepped density distribution with the spectra for the Gaussian distribution. All our calculations were carried out for h=7mm and 1 nC bunch charge.

We apply this analysis beginning from the phase space distribution obtained after particle tracking through the bunch compressor and the first pass through the linac with CSR and longitudinal wake field effects, using Elegant [6].

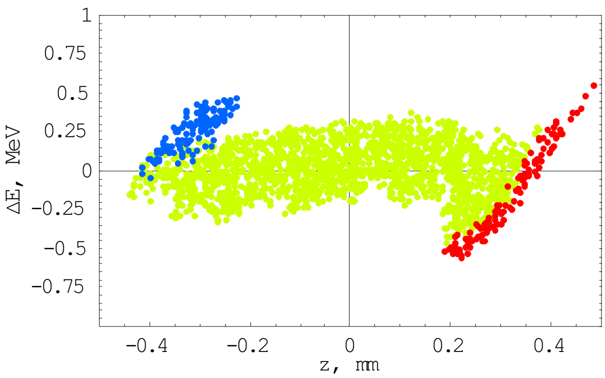

Figure 5. Longitudinal phase space at the end of the first pass through the linac.

This distribution is shown is shown in Figure 5. Red and blue color show approximately 10% of particles from the head and the tail of the bunch. The bulk of the particles are shown with yellow color. One can notice that most distortions are gained in the transition areas of particle density. The longitudinal phase space after the second and the third pass through the linac and at the final energy is shown in Figure 6. Noticeably not much energy spread is gained during the acceleration. We found that the RF phase of 8º for the first beam pass through the linac and RF phases of 5º, 3º, and 6º on subsequent passes are optimal to provide reasonable compensation for correlated energy variations along the bunch induced by the CSR and longitudinal wake field effects.

SUMMARY

The longitudinal dynamics of electrons during the acceleration in the proposed recirculating accelerator LUX has been analyzed. The preliminary results indicate that the machine has sufficient flexibility to be able to counteract and balance effects of coherent synchrotron radiation in the magnetic arcs and the longitudinal wake field effects in the linac. We conclude that the 1 nC electron bunches with bunch length of 2-3 ps can be accelerated to the final energy without excessive growth of the energy spread.

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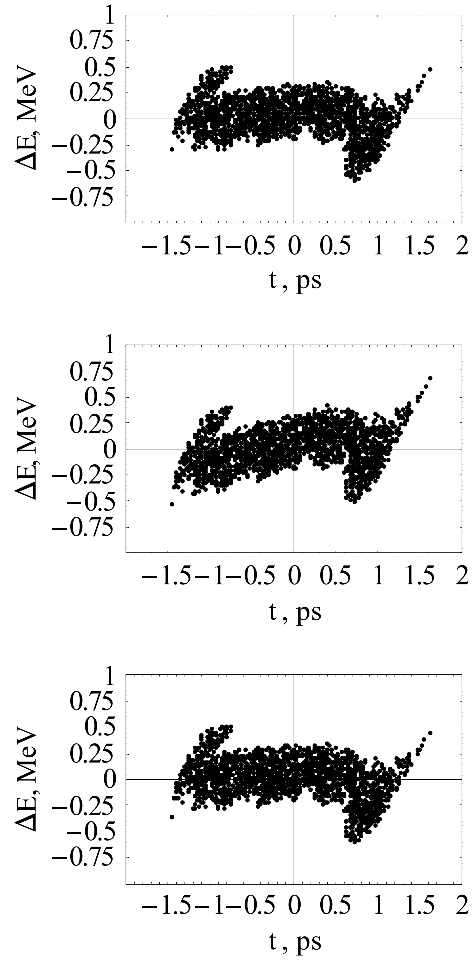

Figure 6. Longitudinal phase space at the end of the second pass through the linac (top plot), third pass through the linac (middle plot) and at the final energy (bottom plot).

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