DEPENDENCE OF LEREC BEAM ENERGY SPREAD ON PHOTOCATHODE LASER MODULATION [*]

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Abstract

Present requirements to the photocathode DC gun of the low energy RHIC electron cooling (LEReC) project is to produce 80 ps long bunch of electrons with charge up to 200 pC. The laser pulse of required length will be produced with the stacking of multiple few picosecond long sub-pulses. Depending on the choice of the laser subpulse length and on the relative delay between these subpulses one can obtain laser pulse with various longitudinal intensity modulations. The longitudinal modulation of laser intensity creates longitudinal modulation of electron bunch charge. Such modulation is known to cause the growth of e-beam uncorrelated energy spread in photoinjectors – the effect we would like to avoid. In this paper we estimate growth of e-beam energy spread due to its initial density modulation and set requirements to the maximum allowable depth of longitudinal modulation of photocathode laser intensity.

INTRODUCTION

The LEReC accelerator [1, 2] consists of a 400 keV photo-gun followed by the SRF Booster, which accelerates the beam to 1.6-2.6 MeV, the transport beamline and the two cooling sections (CS) separated by the 180° bending magnet (see Fig. 1).

Electron bunches are produced by a “beer-can” 80 ps long laser pulses. The flat-top 80 ps long laser is obtained through the stacking of 32 sub-pulses; hence, the laser pulse is modulated in intensity. This modulation is imprinted on the longitudinal distribution of the e-beam charge.

It is known that in the linacs the modulation of longitudinal charge density causes increased energy spread [3-5] and under certain conditions leads to microbunching instability [6-13].

The LEReC e-beam RMS energy spread in the cooling section is required to be below 5e-4. Hence, it is important to estimate the effect of the initial modulation of longitudinal charge density on the resulting energy spread of the beam in the cooling section.

LONGITUDINALY MODULATED BUNCH IN SPACE CHARGE DOMINATED TRANSPORT LINE

Dynamics of premodulated electron bunch has been intensively studied for typical FEL photoinjectors.

Initial longitudinal density modulation of e-bunch is transferred into energy modulation via longitudinal space charge (LSC) field (other self-fields such as CSR or linac wakes can cause similar effect). The induced energy modulation is transferred into even larger density modulation through momentum compaction (R56) of the bunch compressor, thus, creating the microbunching instability [3-13]. This process is repeated for several stages of bunch compression. As a result, even small initial modulation of electron bunch density can cause huge energy modulations of the final bunch as well as 100% modulation of its density.

LEReC photoinjector differs from FEL photoinjectors in two crucial ways. First, its kinetic energy is just 1.6 MeV. So, unlike in FEL photoinjectors the e-bunch longitudinal phase space in LEReC transport line is not frozen at early stages of acceleration and its dynamics is dominated by the space charge. Second, in LEReC the e-bunches are stretched rather than being compressed. Thus, as will be shown below, the microbunching instability is not happening in LEReC.

The current of longitudinally modulated e-bunch can be written as:

$$I = I_0(1 + \rho \cos(kz)) \tag{1}$$

Here, average bunch current $I_0 = \frac{Q_b}{\Delta t_b}$, Q_b is the bunch charge and we assume that modulation wavelength $\lambda = 2\pi/k$ is much shorter than the bunch length $c\Delta t_b$.

The LSC field is:

$$E_{LSC} = -\frac{\partial I}{\partial z}\frac{|Z_{LSC}|}{k} \tag{2}$$

where the LSC impedance is given by:

$$|Z_{LSC}| = \frac{Z_0}{\pi k r^2}\left(1 - \frac{kr}{\gamma}K_1\left(\frac{kr}{\gamma}\right)\right) \tag{3}$$

Here r is bunch radius, $Z_0 = 377\ \Omega$ is free space impedance and K_1 is a modified Bessel function of 2nd kind.

The energy modulation acquired over travel distance Δs is $\Delta\gamma = eE_{LSC}\Delta s/(mc^2)$ therefore from (1) and (2):

$$\frac{d\delta}{ds} = -\frac{4\pi}{\gamma}\frac{I_0}{I_A}\frac{|Z_{LSC}|}{Z_0}\rho \tag{4}$$

where Alfven current $I_A = 17$ kA and $\delta = \Delta\gamma/\gamma$.

In the drift of length Δs momentum compaction $R_{56} = \Delta s/\gamma^2$ converts energy modulation with wavenumber k into bunch current modulation:

$$\frac{d\rho}{ds} = \frac{k}{\gamma^2}\delta \tag{5}$$

Equations (4) and (5) describe LSC induced oscillations of bunch density and energy modulations in longitudinal phase space. From (4) and (5) we obtain a well-known formula for LSC oscillation frequency:

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[*] Work supported by the US Department of Energy under contract No. DE-SC0012704

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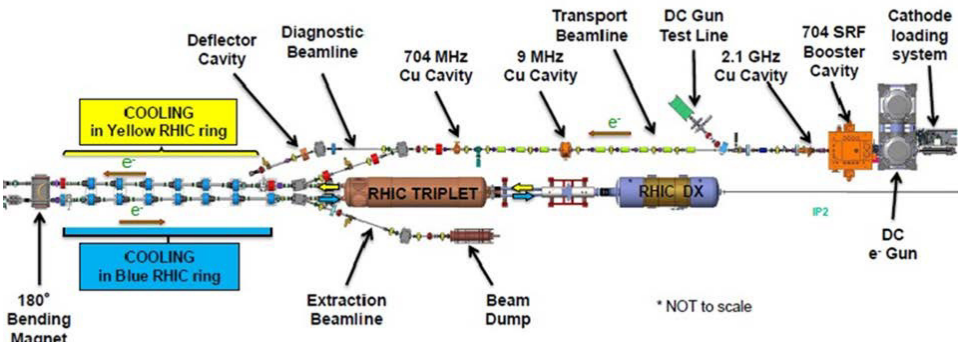

Figure 1: LEReC layout.

$$\Omega=\sqrt{\frac{4\pi k}{\gamma^3}\frac{I_0}{I_A}\frac{|Z_{LSC}|}{Z_0}} \quad (6)$$

From (4) and (6) the maximum energy modulation amplitude (depending on initial density modulation ρ_0) is:

$$|\delta_{max}|=\frac{4\pi}{\gamma\Omega}\frac{I_0}{I_A}\frac{|Z_{LSC}|}{Z_0}\rho_0=\sqrt{\frac{4\pi\gamma}{k}\frac{I_0}{I_A}\frac{|Z_{LSC}|}{Z_0}}\rho_0 \quad (7)$$

EVOLUTION OF BEAM LONGITUDINAL DENSITY MODULATION IN LEREC

Nominal parameters of the LEReC 1.6 MeV electron bunch are given in Table 1. The studies of evolution of bunch modulation for other settings are in progress.

Table 1: LEReC Electron Bunch Parameters

Relativistic gamma factor	γ	4.1
Equivalent radius [mm]	r	8
Bunch charge [pC]	Q_b	130
Initial bunch length [ps]	Δt_b	80
Modulation wavelength [ps]	λ/c	2.5

Substituting parameters from Table 1 into (3) one obtains 223 Ω LSC impedance for LEReC beam.

From (7) we estimate that the RMS value of maximum increase in the e-bunch uncorrelated energy spread due to initial longitudinal modulation of the laser beam is:

$$\delta_{rms}=4.2\cdot10^{-4}\cdot\rho_0 \quad (8)$$

So far, we have been ignoring ballistic lengthening of the beam. Yet, the LEReC scheme of beam transport relies on chirping the bunch in the booster cavity and allowing it to stretch over ~35 m of transport line to the cooling section [14].

Thus, bunch current is reducing along the beamline of length *s* according to:

$$I(s)=\frac{Q_b c}{\Delta t_b c+hs} \quad (9)$$

where $h\approx10^{-3}$ 1/m.

Due to the bunch lengthening effect (4) and (5) become:

$$\begin{cases}\frac{d\delta}{ds}=-\frac{4\pi}{\gamma}\frac{I(s)}{I_A}\frac{|Z_{LSC}|}{Z_0}\rho\\ \frac{d\rho}{ds}=\frac{k}{\gamma^2}\delta\end{cases} \quad (10)$$

with *I*(*s*) given by (9).

Equation (10) can be solved numerically. For convenience we rewrite it:

$$\begin{cases}\frac{dx}{ds}=a(s)y\\ \frac{dy}{ds}=b_0x\\ a(s)=I(s)a_0\\ a_0=-\frac{4\pi}{\gamma}\frac{1}{I_A}\frac{|Z_{LSC}|}{Z_0}\\ b_0=\frac{k}{\gamma^2}\end{cases} \quad (11)$$

Application of implicit method to equations of this type gives stable solution [15]. Explicitly written numeric formulas are:

$$\begin{cases}x_{n+1}=\frac{x_n\cdot(1+w)+y_n\cdot\Delta s\cdot a(s_n)}{1-w}\\ y_{n+1}=\frac{y_n\cdot(1+w)+x_n\cdot\Delta s\cdot b_0}{1-w}\\ w=\Delta s^2\cdot a(s_n)\cdot b_0/4\end{cases} \quad (12)$$

The results of simulations are shown in Fig. 2, with solution of the bunch of constant length shown for comparison.

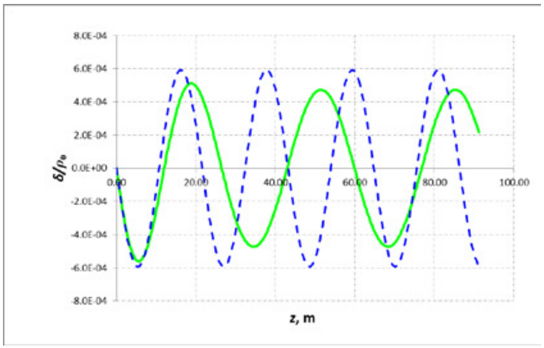

Figure 2: Amplitude of e-bunch energy modulation depending on the path length for ballistically stretched bunch (green solid line) and bunch of constant length (blue dashed line).

As one can see the beam stretching somewhat reduces the expected maximum amplitude of the energy modulation. Hence, equation (8) is still a good estimate from above on the additional RMS energy spread originating from modulation of longitudinal beam density.

OPTIMIZED MODULATION OF LASER PULSE

The requested 80 ps long flat top laser pulse is obtained by pulse stacking 32 green (λ_L = 518 nm) sub-pulses, which lengths can be varied between 2.1 and 2.7 ps. The

LEReC pulse-stacking scheme, schematically demonstrated in Fig. 3, involves 5 birefringent crystals (YVO4).

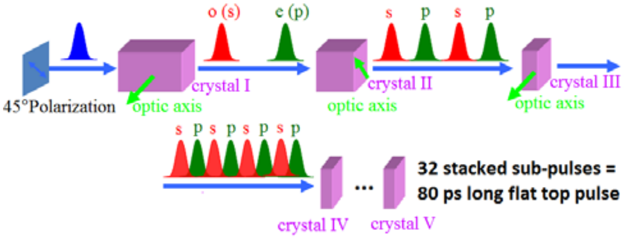

Figure 3: Laser pulse stacking scheme.

Time delay between ordinary and extraordinary pulses in birefringent crystal is:

$$T = L(n_{ge} - n_{go})/c \qquad (13)$$

Here n_{go} and n_{ge} are the group refractive index of the *o*- and *e*-waves, respectively.

Since the group delay difference between the fast and slow optical axis is 1.05 ps/mm, the length of the the first crystal (producing T=40 ps) must be L=38 mm.

Thermal expansion coefficient (*TEC*) of YVO4 is $11 \cdot 10^{-6}$ 1/K. Therefore, the relative phase shift between ordinary and extraordinary pulses in first crystal is:

$$L(n_e - n_o) \cdot TEC \cdot \frac{2\pi}{\lambda} = 1.2 \text{ rad/K} \qquad (14)$$

It follows from (14) that the interference pattern of final sets of ordinary and extraordinary pulses is uncontrollable. Also, orientation of each crystal's optic axis is not perfect 45° with respect to polarization of incoming pulses and can be set only with the precision of about 0.1°. Thus, the phases (relative to each other) of sub-pulses forming the 80 ps long laser pulse are assumed to be random.

We performed dedicated simulations to model the resulting modulation amplitude of 80 ps long pulse depending on the length of stacked sub-pulses. It was determined that the minimum peak-to-peak amplitude ($2\rho_0 = 0.4$) is obtained for sub-pulse with FWHM length of 2.3 ps (see Fig. 4).

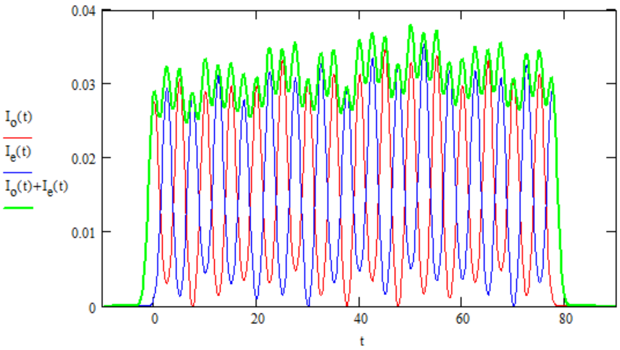

Figure 4: Simulation of stacking of 2.3 ps long (FWHM) sub-pulses with 5 crystals. Red and blue lines respectively represent the intensity of ordinary and extraordinary pulses. Green line shows the resulting intensity of 80 ps long laser pulse. Peak-to-peak amplitude of longitudinal intensity modulation of such pulse is $2\rho_0 = 0.4$.

According to (8) for optimized laser modulation the expected input from e-beam microbunching to the RMS beam energy spread is $\delta_{rms} = 0.8 \cdot 10^{-4}$.

CONCLUSION

In this paper we estimated the growth of LEReC electron beam energy spread due to initial longitudinal modulation of the beam intensity.

In contrary to the intuitive understanding that microbunching severely increases electron bunch energy spread in the space charge dominated photo-injectors we find that for LEReC parameters the microbunching has tolerable effect on overall energy spread of the electron beam. There are two reasons for that.

First of all, the wavelength of the modulation is such that the LSC impedance is relatively small.

Second, the e-bunches in LEReC are stretched rather than being compressed. Thus, the microbunching instability per se is not happening in the LEReC transport line.

We modelled the pulse-stacking process, which is used to create 80 ps long “flat-top” laser pulse illuminating the photocathode. By optimizing the pulse-stacking to minimize the longitudinal modulation of the intensity of the photo-cathode laser we obtained the requirement to stack 2.3 ps long sub-pulses. For such stacking the peak-to-peak amplitude of laser intensity and hence the e-bunch density modulation is 40%. We found that such modulation is still acceptable since its input into RMS relative energy spread is not more than $0.8 \cdot 10^{-4}$.

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