TRANSVERSE ALIGNMENT TOLERANCES FOR THE EUROPEAN XFEL LASER HEATER

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Abstract

We study the impact of misalignments between a laser beam and an electron bunch on the energy distribution function of the electron bunch and on the gain of a microbunching instability in the laser heater. Transverse position and angular misalignment as well as different spot sizes of the laser and electron beam are considered. We find that the transverse misalignment makes the energy distribution function narrower compared to the case of ideal adjustment and a distinct peak in the distribution around the initial mean value of the energy appears. We demonstrate that despite these misalignments a uniform heating in terms of the energy spread can be achieved by appropriately adapting the transverse size and power of the laser beam such that the energy distribution function of the electron bunch at the end of the laser heater can be made similar to a Gaussian, thus providing more effective Landau damping against the microbunching instability. The laser power mainly determines the correlated energy spread while the laser spot size governs the shape of the energy distribution function. The transverse oscillations of electrons induced by the magnetic field in the laser heater are found to be non-essential for typical operation parameters.

INTRODUCTION

A high-energy, high-current electron bunch with a small emittance is a key factor for the successful FEL operation. In order to reach the desired electron peak current, the pulse length of a low-emittance electron bunch generated from the photocathode rf gun is magnetically compressed in the linear accelerator by up to several orders of magnitude. Numerical and theoretical investigations of high-brightness electron bunch compression demonstrate the appearance of a microbunching instability driven by coherent synchrotron radiation (CSR) or by the longitudinal space charge field that can significantly degrade the beam quality [1, 2, 3]. However, the microbunching instability is very sensitive to the uncorrelated energy spread of the electron beam and increasing it within the FEL tolerance can provide strong Landau damping against the instability. To this end, Saldin et al. [4] suggested a laser heater, see Fig. 1, that makes use of resonant beam-laser interaction in a short undulator to induce rapid energy modulation at the optical frequency as an effective energy spread for Landau damping. The proposed method was verified experimentally in [5] and demonstrated to work effectively.

In [3] Z. Huang et al. obtained the expression for the energy distribution function of an electron bunch and calculated the microbunching gain in the case of ideal transverse adjustment between the laser beam and electron bunch. They demonstrated that if the laser spot size is equal to the bunch size, then the energy distribution function is similar to a Gaussian distribution and heating is quite uniform in terms of the energy spread. This allows for the reduction of the microbunching gain. However, some effects having negative impact on laser heater performance like transverse electron wiggling, transverse misalignments and ellipticity of an electron bunch are beyond the scope of the investigation [3]. We address impact of the mentioned above effects on the the European XFEL Laser Heater to the present study and analyze mechanisms of compensation of this impact. To this end, we will first generalize the expression for the energy modulation amplitude. The definition for the energy distribution function obtained in [3] remains unchanged. In what follows, we adopt the nomenclature used in [3].

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ENERGY MODULATION

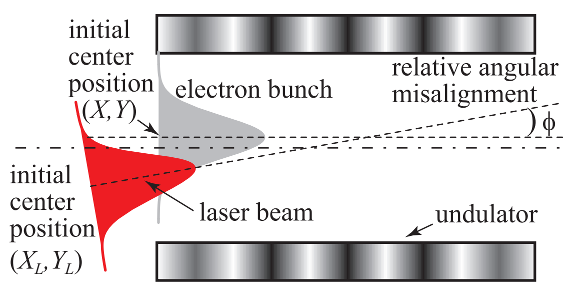

Figure 1: Schematic sketch of the laser heater.

The energy modulation, $\Delta\gamma_L$, induced by the laser beam with Gaussian distribution in the transverse plane reads

$$\Delta\gamma_L \approx \sqrt{\frac{P_L}{P_0}}\frac{\mathcal{K}L_{\rm eff}}{\gamma_0\sigma_L}\tilde{f}(\mathcal{K},x_0)\cos\psi_0\times \exp\Big\{-[(x_0-X_L)^2+(y_0-Y_L)^2]/4\sigma_L^2\Big\}\times e^{A^2/4B}\frac{\sqrt{\pi}}{2\sqrt{B}}\Big[\mathrm{erf}\Big(\frac{A+2BL_{\rm eff}}{2\sqrt{B}}\Big)-\mathrm{erf}\Big(\frac{A}{2\sqrt{B}}\Big)\Big], \quad (1)$$

where

$$A=\frac{(x_0-X_L)\phi_x+(y_0-Y_L)\phi_y}{2\sigma_L^2},\ B=\frac{\phi_x^2+\phi_y^2}{4\sigma_L^2}. \quad (2)$$

Here P_L is the peak laser power, $P_0\approx 8.7$ GW is the universal constant, $\mathcal{K}$ is the traditional undulator parameter, γ_0

is the initial energy of an electron entering the interaction region at transverse position (x_0, y_0) with phase ψ_0, $L_{\rm eff}$ is the effective interaction length, σ_L is the rms laser spot size in the undulator, X_L and Y_L define the position of the center of the laser beam, ϕ_x and ϕ_y are relative misalignment angles between the laser beam and electron bunch in the x and y directions, respectively. The laser wavelength, λ_L, is assumed to satisfy the FEL resonant condition.

The multiplier in the second line of Eq. (1) takes into account the displacement of the laser beam from the symmetry plane of the undulator whereas the multiplier in the third line allows for the relative angular misalignment between the electron bunch and the laser beam. The term $\tilde{f}(\mathcal{K}, x_0)$ is nothing but the modified JJ factor that takes into account the variation of the laser field intensity on the electron trajectory because of transverse and longitudinal wiggling

$$\tilde{f} = 2J_0(\Delta_\parallel)I_1(\Delta_\perp)/\Delta_\perp - J_1(\Delta_\parallel)I_0(\Delta_\perp), \quad (3)$$

where

$$\Delta_\parallel = \frac{\mathcal{K}^2}{4+2\mathcal{K}^2}, \quad \Delta_\perp = \frac{1}{4\sigma_L^2}\left(\frac{\mathcal{K}x_0\lambda_u}{\pi\gamma_0} + \frac{\mathcal{K}^2\lambda_u^2}{2\pi^2\gamma_0^2}\right). \quad (4)$$

Here $J_0(\Delta_\parallel)$ and $I_1(\Delta_\perp)$ are the usual and modified Bessel functions of the first kind. Parameter $\Delta_\perp$ characterizes the reduction in the energy modulation amplitude caused only by transverse wiggling. This reduction is small if $\mathcal{K}\lambda_u/\gamma_0 \ll \sigma_L$, i.e. the amplitude of transverse oscillations is much smaller than the laser spot size.

Eq. (1) together with the definition [3] for the energy distribution function, $V(\Delta\gamma_0)$, allows one to study the impact of transverse misalignments and electron wiggling on the electron energy distribution function. In turn, the electron energy distribution changes the growth rate of the microbunching instability and, thus, determines the effectiveness of the laser heater.

DISTRIBUTION FUNCTION AND MICROBUNCHING GAIN

In the present paper we examine the case of a low bunch charge that is around 0.1 nC with a normalized emittance of 0.33 μm. To achieve a required peak current of 5 kA to drive the European XFEL a strong compression by a factor of around 900 will be applied. The strong compression requires a very small uncorrelated energy spread before the compression in a chicane. In order to obtain the uncorrelated energy spread of 2.4 MeV after the compression the maximal acceptable uncorrelated energy spread before the compression is found to be 3 keV whereas the initial uncorrelated energy spread produced by a photocathode gun is several hundreds of eV and in our simulations it is assumed to be 230 eV. In this case, the required laser power is rather moderate. On the other hand, for a relatively large bunch charge a weaker compression is used and the required energy spread at the exit of the laser heater is of several tens of keV [5] such that the required laser power is in the MW range.

We assume the longitudinal space charge effects to be a primary source of the microbunching instability in our case. The dependence of the microbunching instability on coherent synchrotron radiation will be presented elsewhere. Space charge impedances are calculated for a typical beta function of 20 m. The energies, compression factors and longitudinal momentum compactions factors are 130 Mev, 3.5, 71 mm for the first compression stage; 700 MeV, 8.0, 50 mm in the second stage and 2.4 GeV, 31, 20 mm in the last stage. The linear gain model [6] is based on the integral equation method [2, 3].

As we already mentioned, if the laser spot size is matched to the bunch size $\sigma_x = \sigma_y \approx \sigma_L$, then the energy distribution is similar to a Gaussian distribution for any P_L, see Fig. 2, and the 'heating' is quite uniform in terms of the energy spread [3]. Such heating allows one to reduce substantively the microbunching gain as it is demonstrated in

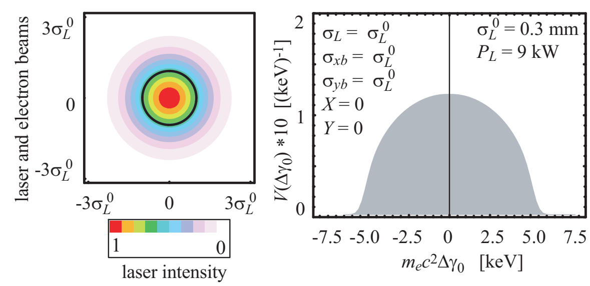

Figure 2: The electron energy distribution for the laser spot size matched to the bunch size. All geometrical quantities are measured with respect to some reference value, σ_L^0, equaling 0.17mm. The solid black circle on the left figure stands for the laser rms spot size. Parameters are $\mathcal{K} = 1.9$, $\lambda_u = 7.4$ cm, $m_ec^2\gamma_0 = 130$ MeV, $\sigma_{\gamma 0} = 230$ eV, $P_L = 3$ kW, $\lambda_L = 1050$ nm, $L_{\rm eff} = 59.2$ cm.

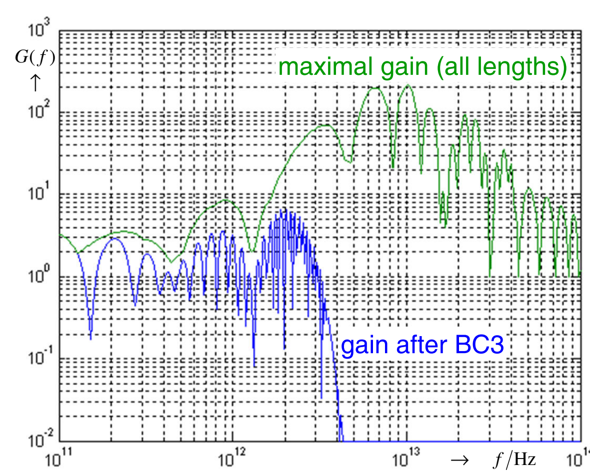

Figure 3: The microbunching gain for the laser spot size matched to the bunch size. See the caption in Fig. 2 for the parameters.

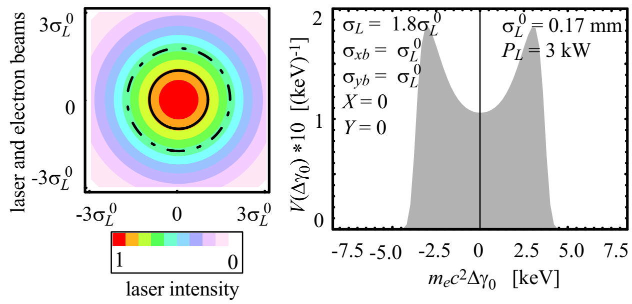

Figure 4: The electron energy distribution for the oversized laser beam. The dashed curve on the left figure stands for the laser rms spot size.

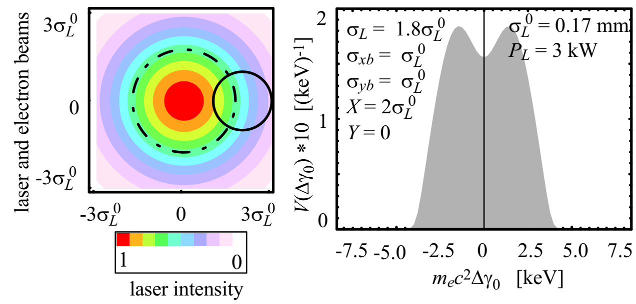

Figure 6: Electron energy distribution for the oversized laser beam. The laser position is adjusted to reduce the microbunching gain.

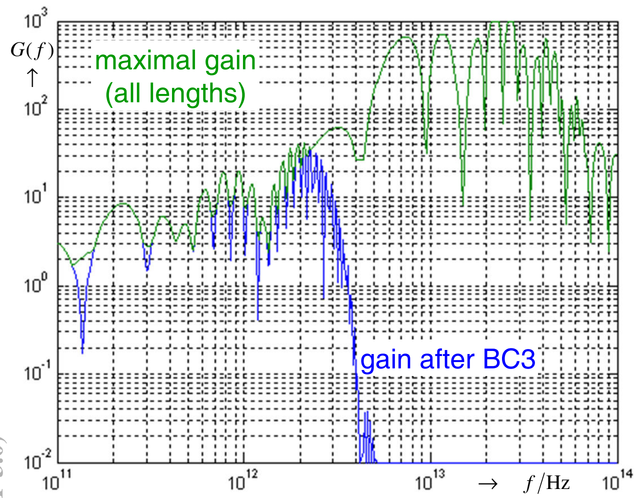

Figure 5: The microbunching gain for the oversized laser beam. For the parameters see Fig. 4.

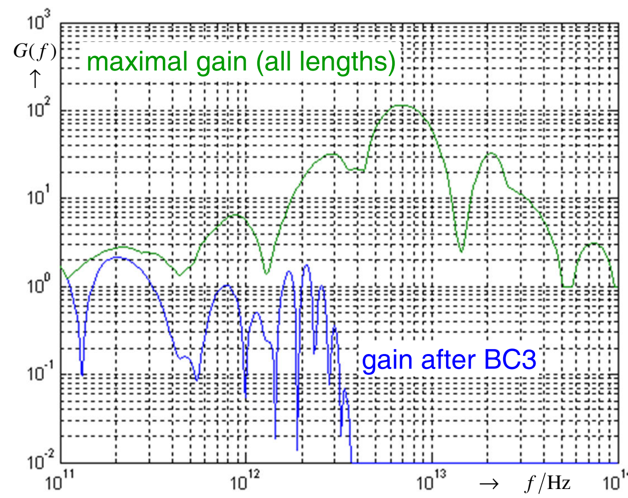

Figure 7: The microbunching gain for the oversized laser beam with the optimized transverse shift. For the parameters see Fig. 6.

Figure 3, where the gain of the microbunching instability in the third bunch compressor and the total gain are presented. One can see that the gain factor for the third compressor is usually of the order of 10 or below. But the maximal gain, which might be reached in lower compression stages, can be dramatically higher up to 1000. Therefore, even very weak initial modulations may cause undesired saturation and non-linear effects increasing the longitudinal and transverse emittances.

The matched case, see Fig. 3, is effective in the sense of suppression of the microbunching instability. In other cases, the microbunching gain is typically higher as it is demonstrated in Figs. 4, 5 where the electron energy distribution and gain for the oversized laser beam are presented. At the same time, by adjusting the laser transverse position one can substantially reduce the gain even below the level typical for the matched case, see Figs. 6, 7. Thus, the suppression of the microbunching instability can be very effective even without matching, cf. Figs. 3, 5, 7.

CONCLUSION

Despite transverse misalignments between a laser beam and an electron bunch a uniform heating in terms of the energy spread can be achieved by appropriately adapting the transverse size/position and power of the laser beam such that the energy distribution function of the electron bunch at the end of the laser heater can be made similar to a Gaussian, thus providing more effective Landau damping against the microbunching instability.

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REFERENCES

[1] E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov, Nucl. Instr. and Meth., Sec. A, vol. 490, p. 1 (2002);

[2] S. Heifets, G. Stupakov, S. Krinsky, Phys. Rev. ST Accel. Beams 5, p. 064401 (2002);

[3] Z. Huang et al, Phys. Rev. ST Accel. Beams, vol. 7, p. 074401 (2004);

[4] E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov, Nucl. Instrum. Meth. A, vol. 528, p. 355 (2004).

[5] Z. Huang et al., Phys. Rev. ST Accel. Beams, vol. 13, p. 020703 (2010);

[6] M. Clemens, S. Lange, M. Dohlus, T. Limberg, G. Poplau, U. van Rienen, TESLA-FEL-2009-02.