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Pulse Length Control in an X-Ray FEL by Using Wakefields

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For the users of the high-brightness radiation sources of free-electron lasers it is desirable to reduce the FEL pulse length to 10 fs and below for time-resolving pump and probe experiments. Although it can be achieved by conventional compression methods for the electron beam or the chirped FEL pulse, the technical realization is demanding. In this presentation we study the impact of longitudinal wakefields in the undulator and how their properties can be used to reduced the amplifying part of the bunch to the desired length. Methods of actively controlling the wakefields are presented.

1. Introduction

With the realization of the 4th generation light sources LCLS[1] and TESLA FEL[2] in the X-ray regimes, new experiments in various fields of science will become possible[3]. In particular, there is an interest in short x-ray pulses for femtochemistry or imaging of single molecules. The pulse lengths of these X-ray FELs are too long (e.g. 230 fs for LCLS) to be sufficient for these classes of experiments, which require a pulse length of around 10 fs.

In general, undulator wakefields degrade the FEL performance[7] by shifting parts of the bunch outside the FEL energy resonance condition. Because the cooperation length of an X-ray FEL is small, undulator wakefields have a ‘local’ effect on the electron bunch. As a consequence, spontaneous radiation is amplified only for those parts of the bunch where wakefield energy loss is compensated by undulator tapering. In this paper, we investigate the wakefield effects (Sec. 2) and how different current profiles or vacuum chamber materials can be used to achieved short FEL pulses (Sec. 3). they can be used to achieved short FEL pulses. The discussion is centered on the LCLS project ($\gamma_0 = 280774$, $I_p = 3.4$ kA, $e_n = 1.2$ mm·mrad and $\sigma_\gamma = 6 \cdot 10^{-5}$ %).

2. Wakefields Effects

Wakefields are generated by the electron bunch as it passes through the undulator vacuum cham-

ber. The amplitude is determined by the dimensions and properties of the chamber. The electrons leave a trailing electric field, which influences the succeeding particles. The dominant wakefield is the resistive wall wakefield due to a finite electric conductivity σ of the chamber wall. The interaction strength is expressed by the single particle wake potential[4]

$$W_s(z) = -\frac{4cZ_0}{3\pi R^2} \left(e^{\frac{z}{\zeta}} \cos \left[\sqrt{3} \frac{z}{\zeta} \right] - \frac{\sqrt{18}}{\pi} \int_0^\infty \frac{x^2 e^{\frac{z}{\zeta} x^2}}{x^6 + 8} dx \right) \quad (1)$$

where the bunch tail is in the direction $z < 0$, c is the speed of light, Z_0 is the vacuum impedance, R is the beam pipe radius and

$$\zeta = \left[\frac{2R^2}{Z_0\sigma} \right]^{\frac{1}{3}} \quad (2)$$

is the characteristic length of the resistive wall wake potential. In the ultra-relativistic approximation, preceding electrons are not influenced by the electron and thus $W_s(z > 0) = 0$.

For the LCLS design case with a radius of $R = 2.5$ mm and a copper plated chamber $\sigma = 5.8 \cdot 10^7 \Omega^{-1}\text{m}^{-1}$, the characteristic length is $\zeta = 8.3 \mu\text{m}$, an order of magnitude smaller than the LCLS bunch length.

Other types of wakefields arise from changes in the vacuum chamber geometry [5] or surface roughness [6]. For typical LCLS parameter their amplitudes are two orders of magnitude smaller than the resistive wall wakefields. Although these

wakes have no impact on the FEL pulse length, their are included in the simulations for completeness.

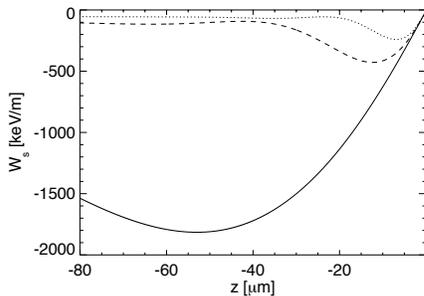


Figure 1. Wake potential for copper, steel and graphite vacuum chamber and a 3.4 kA step profile (dotted, dashed and solid line, respectively).

The single particle wake potentials are convoluted with the current profile. If the profile exhibits any structure on a scale compared to or smaller than the characteristic size of the single particle potential the total wake potential is strongly enhanced by this coherence effect. As an example, Fig. 1 shows the total wake potential for the LCLS uniform step profile and different conducting materials for the vacuum chamber, assuming expected parameters for the geometric and surface roughness wake. The potential is dominated by the resistive wall wake fields and the location of the transition minimum is approximately the characteristic length ζ away from the head ($z = 0$). Within the transition region of the first 15 μm , the wake potential has minimum value of -250 keV/m before it levels out at -30 keV/m for the main part of the bunch.

The undulator wakefields are distinguished from the wakefields in the main linac, because they effect the FEL processes dynamically by changing the electron energy during FEL interaction. While these wakefield is similar to the incoherent emission of undulator radiation, the

energy change varies along the bunch in the case of wakefields. A specific energy loss rate is compensated only by an undulator field taper given by, $da_u/ds = (a_u^2 + 1)/(\gamma a_u)d\gamma/ds$ with s the position within the undulator. Due to the variation in the wake potential only parts of the bunch remains in resonance with the field. The ‘local’ amplification is degraded if the electrons are shifted outside the acceptance of the FEL bandwidth before reaching saturation. The acceptance is given by

$$\left| \frac{d\gamma}{ds} - \frac{\gamma a_u}{a_u^2 + 1} \frac{da_u}{ds} \right| < \frac{\rho^2 \gamma}{\lambda_u} \quad (3)$$

where ρ is the FEL parameter[8] and λ_u is the undulator period.

For LCLS, the bandwidth is 100 keV/m around the compensated energy gradient. In the standard case of the copper-plated vacuum chamber, the head of the bunch does not radiate because the local wake potential lies outside the acceptance of 100 keV/m.

On the other hand, if the acceptance bandwidth is centered around a unique value of the wake potential by a proper choice of the undulator taper, then only a short subsection of the bunch can be selected for lasing. In the following we discuss different conducting material or bunch profiles and how it can be used to achieved short FEL pulses.

3. Current Profiles

In the following we analyse several current profiles, how suitable they are for achieving short FEL pulses. We also consider steel or graphite as the vacuum chamber material, if the standard case of copper is not sufficient enough to achieve short FEL pulses.

The wake potential for copper, steel and graphite are shown in Fig. 1. For copper most of the wake potential lies within the acceptance of 100 keV/m, except for the large amplitude at the head of the bunch. By tapering for the maximum energy loss most of the bunch would not saturate. The minimum amplitude of about 250 keV/m correspond to an overall taper of 0.2% of the magnetic field. The size of the pulse is about

16 μm for over taper between 0.16% and 0.2%. Weaker taper gradients splits gradually the pulse into two. As for copper the taper for a steel vacuum chamber has to compensate the minimum of the wake potential (400 keV/m) to achieve a single, short FEL pulse. The pulse length is 20 μm or larger because the wake minimum is less curved ($\zeta = 29 \mu\text{m}$) than for copper. The area, which lies within the acceptance bandwidth, is longer. A graphite vacuum chamber generates large wake amplitudes. The region of a compensated wake amplitude between 0 and 1.2 MeV/m occurs only once along the bunch. The resulting FEL pulse length is below 5 fs FWHM and insensitive to the taper gradient (Fig. 2).

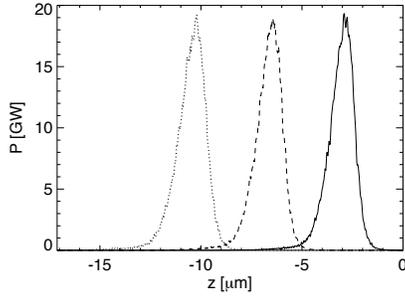


Figure 2. FEL pulse at undulator exit for different overall taper of 0.2%, 0.4% and 0.6% (solid, dashed and dotted line, respectively). The wake potential is based on a step profile and a graphite vacuum chamber.

Gaussian current profiles at LCLS are impractical for achieving short FEL pulse by using wakefields. The copper and steel wake potential remains within the acceptance bandwidth over the entire bunch length. For graphite the position of the wake minimum is close to the part of the bunch with peak current. The wake potential does not cross the acceptance bandwidth with a steep slope as it is case for the step profile discussed above. Only a very strong compression

below a rms size of 15 μ separates the minimum of the wake potential and the maximum of the current far enough, so that at the latter position, the wake potential is steep enough to obtain an FEL pulse length below 25 fs.

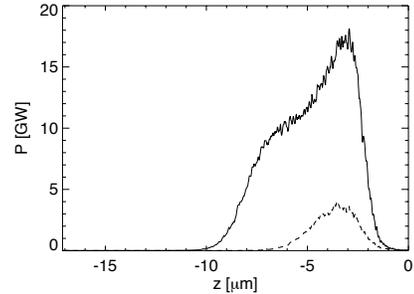


Figure 3. FEL pulse at undulator exit for different bunch lengths of the exponential current profile (20 μm rms size – solid line, 10 μm rms size – dashed line).

Exponential current profiles $I(z) = I_0 \exp[z/\sigma_z]$ are used as an approximation for a strongly compressed bunch. The wake potential is similar to that for the step profile although we are not required to taper for minimum amplitude using a copper plated vacuum chamber. A weaker taper would select two regions of compensated wake fields, but due to the asymmetry in the currently one region has a better amplification. The local current at the other region is below the minimum current, needed for saturation. To guarantee a noticeable effect by this asymmetry the rms bunch length must be comparable to the characteristic length of the potential ($\zeta = 8.3 \mu\text{m}$ for copper). Fig. 3 shows the results for two beam sizes of 10 μm and 20 μm . Although 10 μm case does not reach saturation because the effective current was below 3 kA the FEL pulse length is 10 fs FWHM without the need to change the vacuum chamber material for LCLS design case to a poorer conducting material.

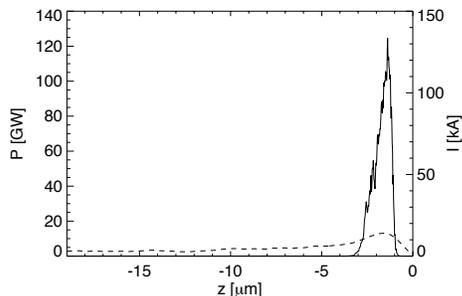


Figure 4. FEL pulse and current profile (solid and dashed line, respectively) at undulator exit, based on a start-end simulation.

Simple profiles, as discussed in the previous paragraphs, are very unlikely to be generated, because space charge, rf curvature, wakefields, and coherent synchrotron radiation in the compressor affects the electron beam quality before injected into the undulator. To estimate a realistic profile a start-end simulation is employed, using PARMELA and ELEGANT, to generate a fully 6 dimensional phase space distribution, which is imported into GENESIS 1.3 and propagated through the undulator. In the LCLS standard case, the rf curvature and wakefields, combined with two stages of bunch compression, the simulation predicts large spikes in the current distribution at the head and tail of the bunch. While the tail spike has no impact for our discussion, the head spike has a width shorter than 10 microns while the peak current reaches almost 15 kA. This spike has less than 10% of the total charge it but doubles the wake amplitude for a copper-plated vacuum chamber as compared to a uniform distribution. The maximum resistive-wall wakefield amplitude is 500 keV/m. Although the beam current does not drop below 3.5 kA, the emittance and energy spread in this region is large enough to inhibit the FEL amplification. Choosing an overall taper of 0.4% results in a FEL pulse length of 5 fs FWHM as shown in Fig. 4. The pulse length is insensitive up to a 15% variation in the current

or taper. In addition, the higher peak current allows a higher saturation power than for the step profile.

4. Conclusion

It has been shown that the combination of undulator wake potentials and undulator field taper can select a short subsection of the bunch to reach saturation. The use of a poor conductor (e.g. graphite) as the vacuum chamber material allows a much more stable operation. The disadvantage is that the FEL cannot operate in short and long pulse mode without changing the vacuum chamber.

Another solution is to manipulate the current profile. If edges or spikes with a size smaller than the characteristic length of the wakefield are present, the wakefield amplitude is locally enhanced. The selection by the acceptance bandwidth of the field taper gets shorter. The pulse length can be further reduced if the beam properties such as current, energy spread or emittance varies over the selected part of the bunch.

Start-end simulation has shown for the LCLS, it is possible to achieve an x-ray pulse length of 10 fs or shorter. It requires a modest tapering of 0.5%.

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