LCLS–TN–98–2
March 1998
SLAC/AP–109
November 1997

Ion Effects in the LCLS Undulator[1]

Frank Zimmermann

Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

Abstract

I calculate the number of ions generated during a bunch passage in the 100-m long undulator of the LCLS X-ray FEL, discuss the emittance dilution caused by these ions, and estimate the acceptable vacuum pressure.

1 Introduction

In this note, I study the ion production by the beam and by the synchrotron-radiation photons during a bunch passage in the LCLS undulator [1] and I investigate three different mechanisms of emittance dilution induced by these ions. From the calculated emittance growth I then estimate the acceptable vacuum pressure for FEL operation. Relevant parameters for the LCLS X-ray FEL are summarized in Table 1.

2 Ionization Processes

There are three conceivable mechanisms by which ions can be created:

1. *Collisional ionization by the beam:* A typical ionization cross section for a GeV electron beam and carbon monoxide or nitrogen gas is of the order of 2 Mbarn[2]. The 2-Mbarn cross section translates into an ion line density of about

$$\lambda_{ion}\,[\mathrm{m}^{-1}] \approx 5 N_b\; p[\mathrm{Torr}] \tag{1}$$

   at the end of the bunch, or 320 ions per meter for a pressure of 10 nTorr.

2. *Ionization by incoherent synchrotron radiation*: The ionization cross section of 8-keV photons for typical elements is about 100 barn [2]. Even though the number of photons at 1.5 Åis three orders of magnitude higher than the number of electrons, this cross section is so much smaller than the collisional-ionization cross section that the photoionization at Angstrom wavelengths can be neglected in comparison.

[1]Work supported by the US Department of Energy under contract DE–AC03–76SF00515.

[2]The ionization cross section for hydrogen molecules would be approximately 10 times smaller.

parameter	symbol	value
beam energy	E	15 GeV
transverse rms beam size	$\sigma_{x,y}$	25 μm
rms bunch length	σ_z	20 μm
charge per bunch	Q_b	1 nC
electrons per bunch	N_b	6.3×10^9
norm. beam emittance	$\gamma\epsilon_{x,y}$	1 μm
average beta function	$\beta_{x,y}$	~ 18 m
no. of wiggler periods	N_p	3328
length of wiggler period	λ_w	3 cm
bend angle per wiggler half period	θ_w	20 μrad
FEL wavelength	λ	0.15 nm
coherent photons per pulse	N_γ	5×10^{12}
undulator length	L_{und}	100 m
saturation length	L_{sat}	94 m
FEL gain length	L_{gain}	10 m
slippage length	L_{slip}	0.5 μm

Table 1: Some parameters of the LCLS X-ray FEL.

In addition to the photons emitted at the first (and higher) FEL harmonic wavelengths, a broad spontaneous photon spectrum extends to much lower energies, where the photoionization cross section is considerably higher: Below about 100 eV the photoionization cross section becomes comparable to, and may even exceed by up to a factor of 5, the cross section for collisional ionization. From Fig. 6 in Ref. [1], illustrating the spontaneous photon spectrum, and from Fig. 1 (next page), showing its low-energy part, I estimate that, at the end of the undulator, there are about 6×10^{10} photons per bunch with energies below 1 keV, and fewer than 5×10^9 photons whose energy is below 100 eV. Thus, the number of low-energetic photons is about equal to the number of electrons in the bunch. With an rms opening angle of 10–20 μrad for the spontaneous radiation (and an even wider opening angle at low photon energies), the photoionization processes occur on average far away from the beam orbit. Therefore, and considering the small number of low-energy photons, we may assume that the ions produced by photoionization form a diffuse halo, whose effect on the beam is negligible compared with that of the much denser ion cloud produced by collisional ionization inside the beam.

3. *Tunneling ionization in the coherent laser field:* Up to frequencies of the order

$$\omega_t = eE/\sqrt{2m_e}I \tag{2}$$

the tunnel effect is determined simply by the instantaneous value of the electric field [4, 5]. In Eq. (2), the parameter E is the electric field, m_e the electron mass, and I the ionization potential. The peak electric field of the laser pulse can be roughly estimated from the equation

$$\hat{E} \approx \left(\frac{2N_\gamma \hbar\omega}{(2\pi)^{3/2}\epsilon_0 \sigma_x \sigma_y \sigma_z} \right)^{1/2} \tag{3}$$

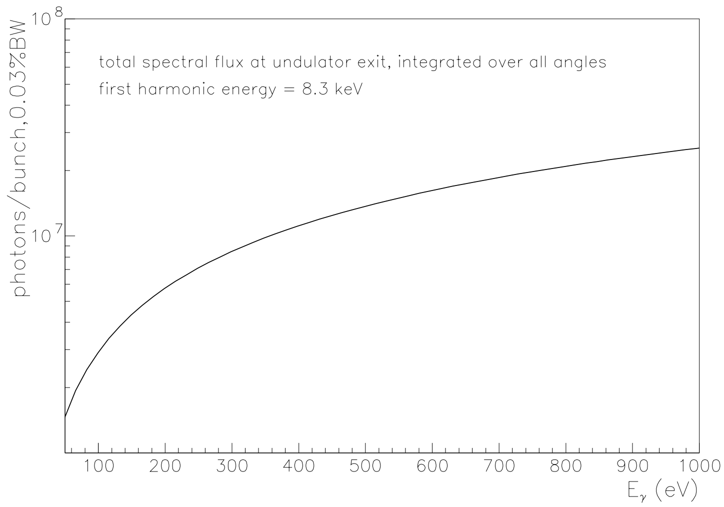

Figure 1: Number of photons per 0.03% frequency interval and per bunch passage at the end of the LCLS undulator [3]; the spontaneous flux increases linearly along the undulator.

and is found to be about 9 GV/m. Somewhat arbitrarily using $I \approx 20$ eV, the threshold frequency is $\omega_t \approx 6 \times 10^{14}$ s^{-1}, which is low compared to the FEL frequency $\omega \approx 10^{19}$ s^{-1}. This means that the standard formula for static tunneling ionization does not apply here.

To determine if the coherence of the FEL X-rays is important, we calculate the photon density,

$$n_\gamma \approx \frac{N_\gamma}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z} \approx 2.5 \times 10^{25} \text{ m}^{-3}, \tag{4}$$

which implies that in a sphere with a radius equal to the Bohr radius a_0 ($a_0 \approx 0.5$ Å) on average there are only 10^{-5} photons at any given time during the pulse. It is thus legitimate to consider the photons as incoherent [6], in which case, as seen under point 2, their contribution to the ionization is insignificant.

3 Emittance Dilution

Ions could dilute the bunch emittance in various ways: first, the ions induce a tune shift across the bunch which could lead to filamentation and to an effective increase in the transverse emittance; second, the electrons or, third, the ions generated by the bunch head can excite the bunch tail and cause a beam break-up instability.

Pessimistically assuming that all electrons originating in the ionization process are dispersed and lost before the end of the bunch[3] one can estimate the ion-induced shift in betatron phase advance

[3]Using this assumption, which is not fulfilled for the LCLS, the actual tune shift will be overestimated.

between head and tail of the bunch at the end of the undulator:

$$\Delta\psi_{\beta_{x,y}} \approx \frac{\beta_{x,y} r_e \lambda_{ion} L_{und}}{\gamma\sigma_{x,y}(\sigma_x + \sigma_y)} \tag{5}$$

Using an ion line density λ_{ion}, as expected for collisional ionization, Eq. (1), the phase shift is $\Delta\psi_{x,y} \approx 4 \times 10^{-6}$ rad for 1 nTorr and 4×10^{-4} rad for 100 nTorr. Significant emittance growth due to filamentation would be expected only for an average pressure exceeding 100 μTorr, for which the phase shift approaches 1 rad.

Since, different from the situation in most other accelerators, the bunch length in the LCLS is shorter than the transverse beam size, the electrons do not escape from the bunch during its passage, but the electrons generated by the head will still affect the trailing particles. The resulting emittance growth can be estimated from a first-order perturbation expansion, in analogy to the treatment in Ref. [7]:

$$\Delta\epsilon_y \approx \frac{\pi^2 N_b \lambda_{ion}^2 r_e^3 \sigma_z L_{und}^2 \hat{y}^2 \beta_y}{54\sqrt{2\pi}\gamma^2\sigma_y^3(\sigma_x + \sigma_y)^3} \tag{6}$$

where $\hat{y}$ describes the amplitude of an initial vertical perturbation of the form $y_b^0(s, z) = \hat{y}\cos(s/\beta + \phi)\sinh(\omega_i z + \theta)$ with[4] $\omega_i \equiv (4N_b r_e/(3\sqrt{2\pi}\sigma_z\sigma_y(\sigma_x + \sigma_y)))^{1/2}$, s is the longitudinal position along the beam line, and z denotes the longitudinal position of a particle with respect to the bunch center. Exactly the same expression with the subindices x and y interchanged applies to the horizontal case, and, by symmetry, it yields the same emittance growth. Inserting numbers and assuming an ion density as in Eq. (1), we can rewrite Eq. (6) as

$$\Delta(\gamma\epsilon_y)\ [\mathrm{m}] \approx 4 \times 10^{-19} \left(\frac{\hat{y}}{\sigma_y}\right)^2 \ (p\ [\mathrm{nTorr}])^2 \tag{7}$$

For a huge perturbation, $\hat{y} \approx 10\,\sigma_y$, one finds that the emittance growth becomes significant when the pressure approaches 10^{-4} Torr, which is almost five orders of magnitude higher than the anticipated operating pressure.

In principle, not only the electrons but also the ions themselves could drive an instability, even though the ions do not move during the beam passage. This could happen when the bunch is tilted and the ions generated by the head are offset with respect to the tail. Especially important is the case when the ion force drives the beam tail in resonance with the betatron motion. As an example, due to the acceleration in the SLAC linac the beams in the SLC arcs usually exhibit a significant energy spread which is correlated with the longitudinal position along the bunch. At locations with vertical dispersion the beam is tilted vertically with respect to the forward direction. Since the vertical dispersion in each achromat of the arc propagates exactly like a betatron oscillation, ions generated by the head then drive the tail in resonance. It was found that this effect sets the tolerance on the acceptable arc vacuum pressure [8]. In the case of the LCLS, effects of this type are unlikely to be important because the horizontal design dispersion in the undulator is tiny. The peak dispersion is only about $\hat{\eta_x} \approx \theta_w l_w/8 \approx 70$ nm, so that any perturbation involving energy variation and dispersion will be very small compared with the transverse beam size.

[4]Inserting numbers, we find $\omega_i\sigma_z \approx 0.3$.

4 Conclusion

In this note I have estimated the number of ions generated during a bunch passage in the LCLS undulator and their effect on the beam emittance. The ionization of the residual gas due to the coherent X-rays and, from the viewpoint of beam dynamics, also the ionization due to the lower-energetic spontaneous photons were found to be insignificant compared with the collisional ionization by the beam. As a result, there does not seem to exist a tight tolerance on the vacuum pressure in the LCLS undulator. Even a pressure as high as 1 μTorr would still appear to be perfectly acceptable.

Acknowledgements

I thank A. Chao and M. Ross for suggesting this study, and P. Chen, P. Emma, H.-D. Nuhn, T. Raubenheimer and R. Tatchyn for helpful discussions. I also thank P. Emma for a careful reading of the manuscript.

References

[1] R. Tatchyn et al., "Research and Development Toward a 4.5-1.5 ÅLinac Coherent Light Source (LCLS) at SLAC", *SLAC-PUB-95-6994* (1995).

[2] D.E. Cullen et al., "Tables and Graphs of Photon-Interaction Cross Sections from 10 eV to 100 GeV Derived from the LLNL Evaluated Photon Data Library (EPDL)", Lawrence Livermore National Laboratory, *UCRL–504000–Vol.6–Rev.4–Pt.A* (1989).

[3] The data for this picture were provided by R. Tatchyn (1997).

[4] L.V. Keldysh, "Ionization in the field of a strong electromagnetic wave", *Soviet Physics JETP*, Vol. 20, no. 5 (1965).

[5] T. Raubenheimer, private communication (1997).

[6] P. Chen, private communication (1997).

[7] T.O. Raubenheimer and F. Zimmermann, "A Fast Beam-Ion Instability in Linear Accelerators and Storage Rings", *Physical Review E*, Vol. 52, 5, pp. 5487–5498 and *SLAC-PUB-6740* (1995).

[8] P. Emma, T. Raubenheimer, F. Zimmermann, "Emittance Dilution by Ions in the SLC Arcs", Proc. of the *Fourth European Accelerator Conference (EPAC 94)*, World Scientific, Vol. 2, p. 1162 (1995), and *SLAC-PUB-6522* (1994).