LCLS-II Technical Note

Laser Heater: Scaling of Laser Power with Undulator Period and Laser Wavelength

LCLS-II TN-14-05

3/25/2014

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1 Introduction

A tentative baseline design for the LCLS-II Laser Heater (LH) was documented in Chapter 7 of the CDR; the relevant parameters are reported in Table 1. (The stated beam emittance is for 100 pC bunches). The purpose of this Note is to review the dependence of the LH performance to certain design parameters (e.g. laser pulse energy vs. laser wavelength), which should be useful toward the adoption of the final specs. The final section (Sec. 5) contains the specifications for an alternate LH design exploiting the exiting $\lambda_u = 5.4$ cm undulator.

Table 1: Laser Heater parameters as in the CDR design

Parameter	Symbol	Value	Unit
Electron beam energy	E	98	MeV
Betatron functions at LH undulator center	$\beta_x = \beta_y$	10	m
Horizontal Twiss function (exit of LH chicane)	α_x	-0.18	-
Normalized transverse emittance used in these LH calculations	$\varepsilon_{nx} = \varepsilon_{ny}$	0.3	μm
Electron beam transverse rms sizes[1] (at LH undulator center)	$\sigma_x = \sigma_y$	125	μm
Chicane dipoles bend angle	$\lvert\theta_B\rvert$	0.102	rad
Chicane dipoles lengths	L_B	0.124	m
Drift from 1st -to-2nd and 3rd -to- 4th dipole	ΔL_1	0.603	m
Dispersion (at undulator)	$\lvert D_u\rvert$	7.5	cm
Horizontal offset of undulator from linac axis	Δx	7.5	cm
Momentum compaction (over full chicane)	$\lvert R_{56}\rvert$	14.5	mm
Undulator gap (minimum 3.0 cm)	g	3.1	cm
Undulator period	λ_u	4.71	cm
Undulator parameter	K	1.1	-
Undulator peak magnetic field	B_0	0.25	T
Number of undulator periods	N_u	10	-
Laser wavelength	λ	1030	nm
Laser pulse transverse rms size (middle of undulator)	σ_r	125	μm
Rayleigh length	Z_R	19	cm
Laser pulse length (FWHM)	T_L	20	ps

[1] Not including the effect of the small $\sigma_\delta = 0.05\%$ energy spread expected in a100pC beam. When this is included $\sigma_x \simeq 130\mu m$.

Beam rms-energy spread induced by Laser Heater (max.)	σ_E	20	keV
Laser pulse energy[2]	E_L	8	μJ
Laser pulse peak power [2]	P_L	0.35	MW

2 Model Equations

The relevant equations are the:

i) **undulator radiation condition**

$$\lambda_L = \frac{\lambda_u}{2\gamma^2}(1+\frac{K^2}{2}) \qquad (1)$$

relating undulator period λ_u, laser wavelength λ_L , electron beam energy, and undulator parameter K;

ii) expression for the **undulator parameter** $\boldsymbol{K}$ as a function of undulator period and peak magnetic field B_0 (expressed here in practical units)

$$K = 0.934 \times \lambda_u[cm] \times B_0[T] \qquad (2)$$

with $B_0 = b\exp(-\frac{ag}{\lambda_u})$ being a good model for a PM undulator ($b = 2.08T$, $a = 3.24$ reproduce fairly well the field in the existing LCLS-I LH undulator); and finally

iii) equation yielding the required **laser pulse peak power** $\boldsymbol{P_L}$ for inducing $\sigma_{E,LH}$ rms energy spread

$$P_L = 2P_0\,(\sigma_x^2+\sigma_r^2)\left[\frac{\gamma\sigma_{E,LH}}{mc^2[JJ]KL_u}\right]^2. \qquad (3)$$

In the last equation $P_0 \simeq 8.7$ GW, $[JJ] = J_0[\xi] - J_1[\xi]$ with $\xi = K^2/(4+2K^2)$, and $\sigma_x = \sigma_y$ and σ_r are the electron beam and laser rms transverse sizes (note that the latter is defined as the laser *intensity* spot size $\sigma_r = w_0/2$,where w_0 is the parameter appearing *e.g.* in the definition of Rayleigh range $Z_R = \pi w_0^2/\lambda_L$). Equation (3) is valid in the approximation that the Rayleigh range is not too short compared to the undulator length $L_u = N_u\lambda_u$ so that diffraction effects can be neglected (in fact, diffraction effects for the proposed design are not completely negligible and give a loss of efficiency on the order of 20%).

3 Laser Power vs. undulator period

For fixed i) beam energy, ii) beam transverse sizes, iii) laser wavelength, iv) number of undulator periods N_u, v) desired heating $\sigma_{E,LH}$ a convenient way to represent the solutions of the three equations above for undulator gap, undulator period, and the laser peak power is to do a parametrization in terms of the undulator parameter K, as in Fig. 1. Here we have assumed that the laser transverse size matches that of the laser ($\sigma_r =$

[2] Includes a factor 2 safety margin meant to account for usage of wider laser spot size $\sigma_r > \sigma_x$.

σ_x). According to Eq. (3) doubling the laser spot size to $\sigma_r = 2\sigma_x$ would increase the laser power requirement by a factor 5/2.

The CDR design parameters are obtained by setting the undulator gap to $g = 3.1\,cm$. From the top-left picture of Fig. 1 this is seen to correspond to $K = 1.1$ and identifies the required undulator period λ_u=4.7 cm (bottom-left picture) and laser pulse peak power (top-right picture) or energy (bottom-right picture). The laser pulse energy E_L is calculated under the assumption of a gaussian laser profile with 20ps FWHM length. In the CDR baseline design this amounts to about $3\mu J$, or about $4\mu J$ once the diffraction effects not captured by Eq. (3) are included. The CDR specification is for $8\mu J$ to leave sufficient overhead to operate with a wider laser spot. (To keep with the convention adopted in the CDR document we use dashed lines in the plots for P_L and E_L to emphasize that diffraction effects are not included.)

Plots of undulator gap and pulse energy as functions of the undulator period are shown in Fig. 2. In the right picture of Fig. 2 the two curves correspond to a choice of $N_u = 10$ (baseline) and $N_u = 9$ number of undulator periods. The CDR baseline design is indicated by the dot. Figs. (3) and (4) show how the laser power requirement decreases for larger beam energies.

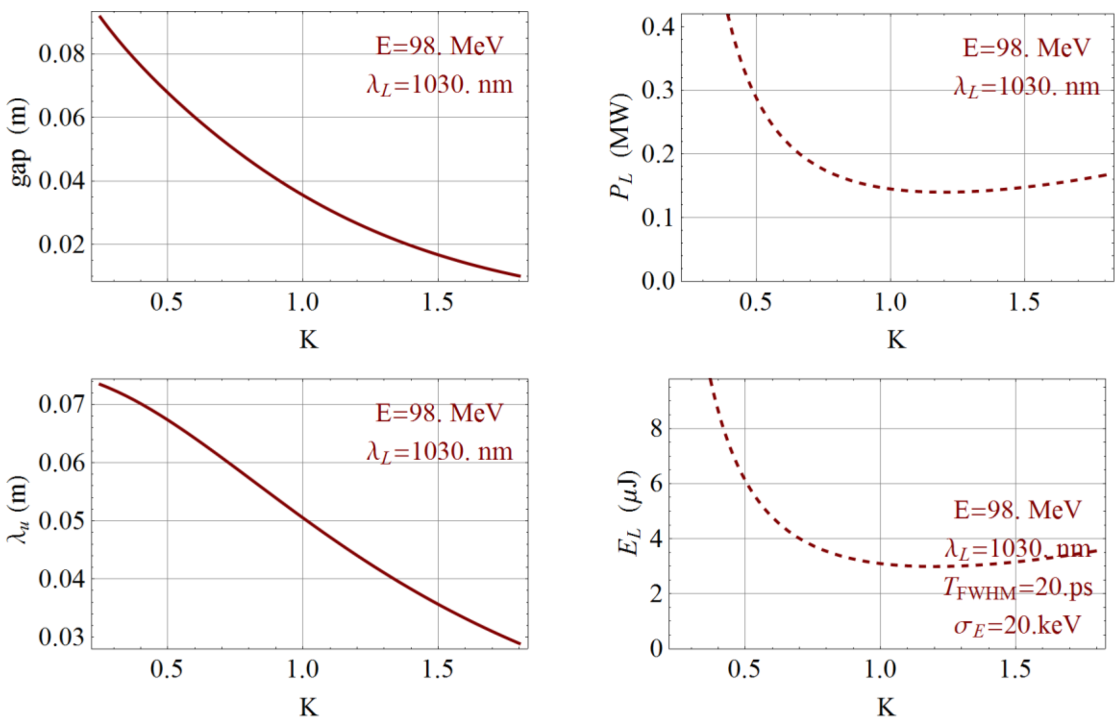

Figure 1 ***Undulator full magnetic gap and period (two pictures on the left) required to satisy the undulator radiation resonance condition in a PM undulator as functions of the undulator parameter. The corresponding laser pulse peak power and energy (a 20ps FWHM gaussian profile is assumed) yielding the desired $\sigma_{E,LH} = 20keV$ heating are shown to the right. Notice that of P_L and E_L display a broad minimum. The rapid loss of efficency observed at low K occurs as a result of the reduced magnetic field; at high K the loss is due to the shrinking length of the undulator $L_u = N_u\lambda_u$ (as N_u is kept fixed here while the undulator period decreases for larger K to maintain the resonace condition). All parameters not explcitly indicated are as in Table 1.***

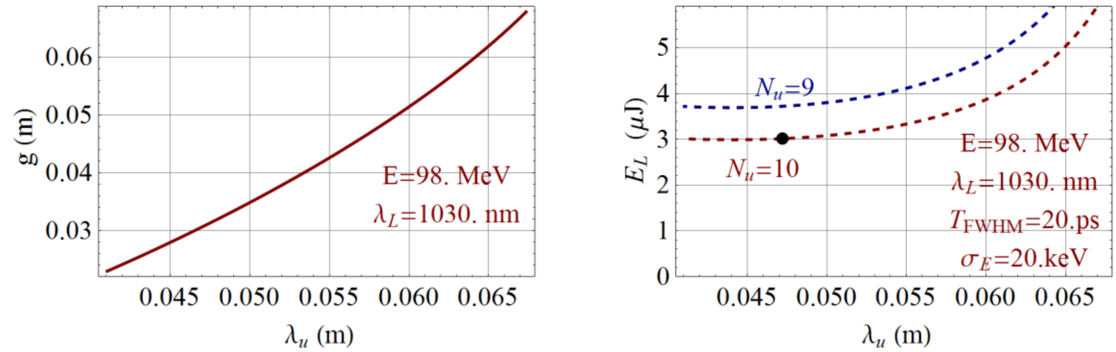

Figure 2 ***Undulator gap and laser pulse energy are shown as functions of the undulator period. In the right picture the required laser pulse is shown for both the CDR baseline undulator with $N_u = 10$ no. of periods, and modified undulator with $N_u = 9$ (as in LCLS-I, where $\lambda_u = 5.4cm$). The dot corresponds to the CDR baseline design.***

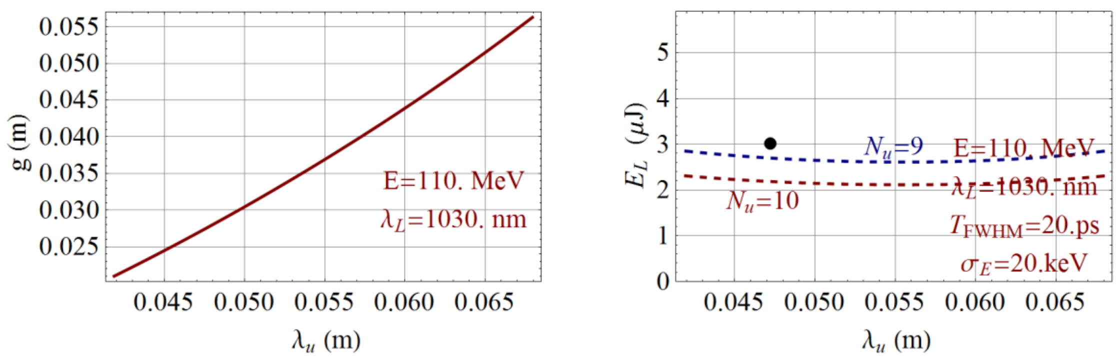

Figure 3 ***Same as Fig. 2 except for the choice of a higher beam energy (110 MeV vs. the 98 MeV CDR baseline design), showing an augmented efficency of about 30%. In addition to the baseline value for no. of period ($N_u = 10$) we show the $N_u = 9$ case as well. The dot corresponds to the CDR baseline design.***

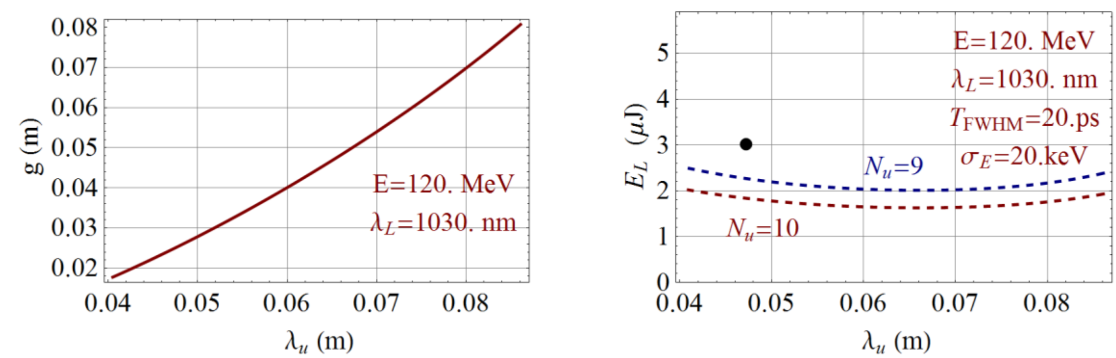

Figure 4 ***Same as Fig. 3 except for the choice of an even higher beam energy (120 MeV) .***

4 Laser power vs. laser wavelength

The laser heater becomes increasingly inefficient for shorter wavelengths, as a smaller undulator parameter K is needed to keep the system on resonance. We study the dependence of the laser pulse energy on choice of laser wavelength by fixing beam energy ($E = 98\ MeV$) and undulator gap ($g = 3.1\ cm$). Fig. 5 shows that a 758 nm laser wavelength (as in in the LCLS-I Laser Heater) would result into an almost factor two loss of efficiency compared to the CDR baseline ($\lambda_L = 1030\ nm$). Fig. 6 reports the undulator period and the undulator parameter meeting the resonance condition as functions of λ_L.

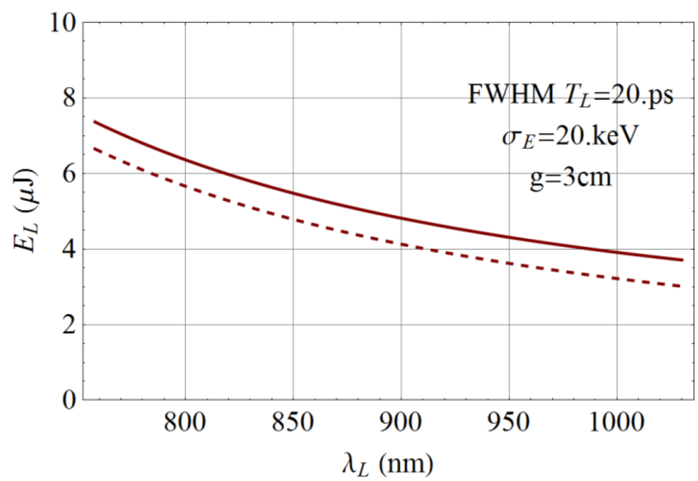

Figure 5 ***Laser pulse energy required to induce $\sigma_E = 20keV$ heating as a function of choice of laser wavelength over the range $\lambda_L = 758nm$ to $1030nm$. The beam energy ($E = 98\ MeV$) and undulator gap ($g = 3cm$) are kept fixed. The laser heater becomes increasingly inefficient at shorter wavelengths as a shorter undulator period and smaller K are required in order to meet the resonance condition (see Fig. 5). The dashed line is from Eq. (3); the solid line accounts for diffraction effects (with some appoximation) due to the finite Rayleigh range.***

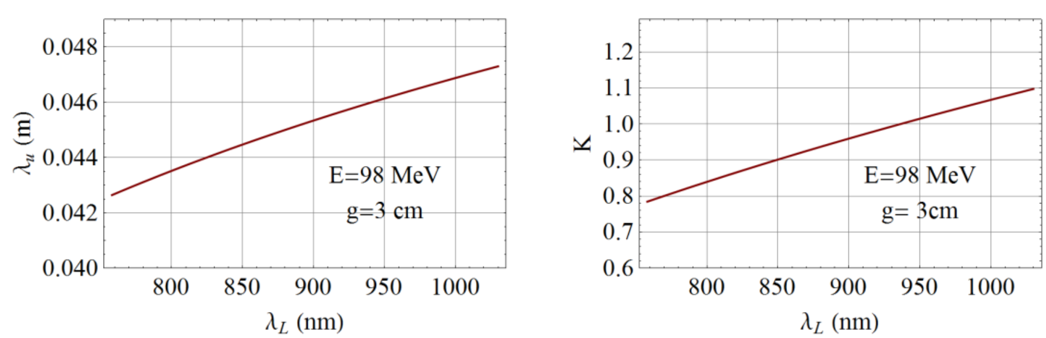

Figure 6 **Undulator period (left) and undulator parameter(right) as functions of the laser wavelength. Beam energy $E = 98MeV$ and undulator gap $g = 3\ cm$ are kept fixed.**

5 LH design based on existing hardware ($\lambda_u = 5.4$cm) @$E_{max} = 120$ MeV

This section contains the specifications for a Laser Heater that would exploit the exiting $N_u = 9$ period, $\lambda_u = 5.4$cm undulator, and operate up to 120 MeV beam energy. The relevant parameters are summarized in Table 2 for E=120 MeV. (The stated beam emittance is for 100 pC bunches). Figure 7 shows how undulator gap, parameter, peak magnetic field, and required laser pulse energy vary over a range of beam energies down to $E = 95$ MeV. Notice that in our calculations we assumed a transverse laser rms spot size that is 50% wider than that of the electron beam to reflect the most likeley operational scenario. The shaded area in the top-left picture identifies the boundaries for 15% efficiency loss off the undulator-radiation resonance.

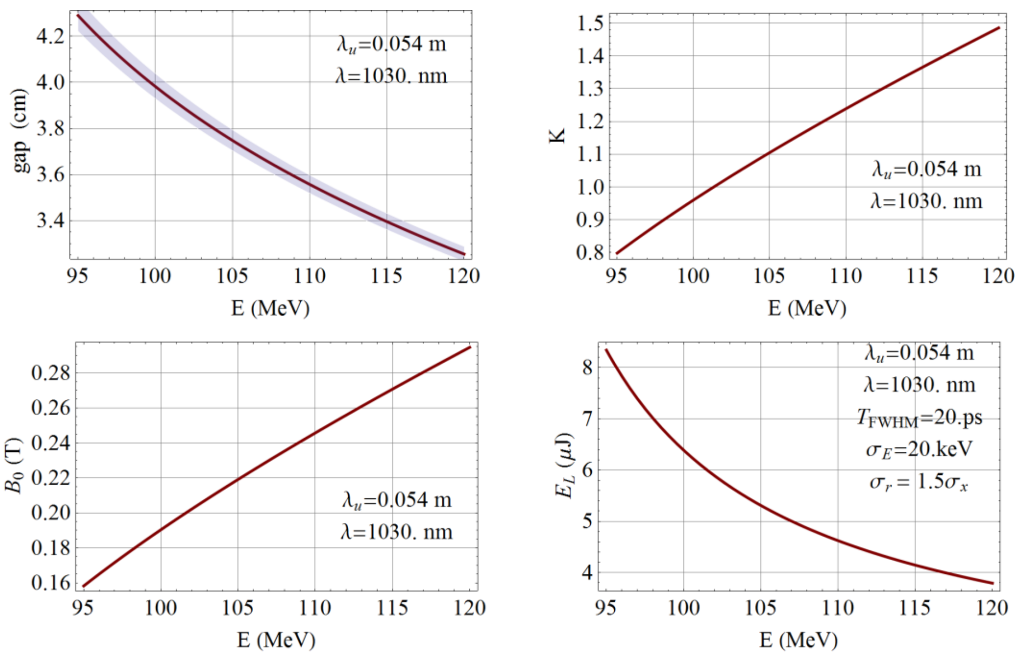

Figure 7 ***Undulator full magnetic gap (top left), undulator parameter (top right), magnetic field (bottom left), and laser pulse energy (bottom right) required for $\sigma_{E,LH} = 20keV$ heating. A 20ps FWHM gaussian profile is assumed for the laser pulse. The laser spot is 50% larger than the beam transverse size $\sigma_r = 1.5\sigma_x$. The beam transverse size scales with energy.***

Table 2: **Alternate Laser Heater design specs based on a $\lambda_u = 5.4$ cm undulator** *(Note: in this table the laser pulse energy and peak power do not include any safety factor. A laser spot size wider than the beam is already in the specs.)*

Parameter	Symbol	Value	Unit
Electron beam energy	E	120	MeV
Betatron functions at LH undulator center	$\beta_x = \beta_y$	10	m
Twiss functions at LH undulator center	$\alpha_x = \alpha_y$	-0.05	

Horizontal Twiss function (exit of LH chicane)	α_x	-0.18	-
Normalized transverse emittance used in these LH calculations	$\varepsilon_{nx} = \varepsilon_{ny}$	0.3	μm
Electron beam transverse rms sizes (at LH undulator center)	$\sigma_x = \sigma_y$	115	μm
Chicane dipoles bend angle	$\|\theta_B\|$	0.102	rad
Chicane dipoles lengths	L_B	0.124	m
Drift from 1^{st} -to-2^{nd} and 3^{rd} -to- 4^{th} dipole	ΔL_1	0.603	m
Dispersion (at undulator)	$\|D_u\|$	7.5	cm
Horizontal offset of undulator from linac axis	Δx	7.5	cm
Momentum compaction (over full chicane)	$\|R_{56}\|$	14.5	mm
Undulator gap	g	3.2	cm
Undulator period	λ_u	5.4	cm
Undulator parameter	K	1.5	-
Undulator peak magnetic field	B_0	0.3	T
Number of undulator periods	N_u	9	-
Laser wavelength	λ	1030	nm
Laser pulse transverse rms size (middle of undulator)	σ_r	172	μm
Rayleigh length	Z_R	35	cm
Laser pulse length (FWHM)	T_L	20	ps
Beam rms-energy spread induced by Laser Heater (max.)	σ_E	20	keV
Laser pulse energy	E_L	4	μJ
Laser pulse peak power	P_L	0.2	MW