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Proposed LCLS Undulator Parameter Modifications

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Introduction

In preparation for the definition of the LCLS Baseline design, the undulator parameters have been reexamined and a number of changes are being proposed. In particular, the 6 mm undulator gap of the CDR design appears to be too small for mechanical and radiation damage related reasons. Also, the break lengths between the undulator modules of about 18 cm and 42 cm are now considered too short and will be increased to about 40 cm and 60 cm, respectively.

During the search for a new gap value it was found that it appears possible to change the resonant wavelength at the highest electron energy of the operational range from the present value of 1.5 Å down to 1 Å while keeping the saturation point before the end of the undulator for the goal emittance of 1.2 mm mrad. The performance for the goal wavelength of 1.5 Å, obtained now at the electron energy of about 11.5 GeV, would change little, i.e., the saturation length would stay unchanged at or below about 90 m but the saturation power would drop by about 4 GW or by one half, which is considered not acceptable for certain experiments. A solution for this problem came recently when it was found that the variable K mechanism (comb structure), that is being investigated for use as fine adjustment control for the average on-axis vertical magnetic field to help complete the shimming process, might have enough additional dynamic range to allow tapering, i.e., stepwise changing the K values of the last 9 undulator modules. The total range over which K could be adjusted by the comb device has been estimated to be about 0.65 %. Tapering the undulator from the saturation point on will increase the production of photons in that region, significantly. At the highest tapering levels, the additional power gained could exceed 30 GW, which would be more than enough to restore the power lost by the gap increase. It is estimated that the required range for the adjustment of the K parameter for the purpose of tapering would be between about 0.2 % and 0.5 %.

In order to maintain support for the full operational wavelengths range of up to 15 Å, it is also necessary to reduce the focal strength of the permanent magnet focusing lattice. The reason for this is that the old focal strength of about 110 T/m for a 5-cm long quadrupole would not allow electron beams of less than about 3 GeV to pass. The proposed change in gap will reduce the electron energy for the 15 Å-wavelength from about 4.5 GeV to 3.6 GeV, which is too close to that lower energy limit. The proposal is to reduce the focal strength to about 60 T/m, which will reduce the lower energy limit of the FODO channel to below 2 GeV.

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This document describes the new values that are being proposed for the undulator period, λ_u, the maximum available linac energy, E_{max}, the undulator magnetic gap, g, and the average beta-function, $\langle \beta_{x,y} \rangle$ at the highest energy, as well as a new break pattern and field taper for the last 9 undulator modules. In summary, the proposed parameter values:

λ_u	3.0 cm
E_{max}	14.1 GeV
g	8.2 mm
$\langle \beta_{x,y} \rangle$ at E_{max}	30 m
Break pattern	3-3-4
Field Taper After Saturation	.2-.5 %

The following sections discuss the changes in more detail.

Corrected On-Axis Undulator Field

Measurements done on the first LCLS prototype undulator show that the on-axis magnetic field is about 5.345% larger than given by the standard Halbach formula for a Nd:FeB Hybrid undulator:

$$B = a\, e^{b\frac{gap}{period}+c\left(\frac{gap}{period}\right)^2} \tag{1.1}$$

with $a = 3.44\,T$, $b = -5.08$ and $c = 1.54$. The standard Halbach formula has been used in the past to estimate the undulator fields. Recently, Elleaume et al. [1] re-evaluated the formula using the RADIA code and, as a result, found a slightly different set of constants, i.e., $a = 3.694\,T$, $b = -5.068$ and $c = 1.520$. Using the Elleaume parameters the measured field is 2.1 % smaller than the estimate.

Period Selection

A change in undulator period would require more man-power and time than is available before the next review. It is therefore desirable to maintain the period length at 3 cm.

Reduction in Maximum Available Energy

In the course of the development of the linac system the available energy has been more and more reduced either by the removal of linac sections or by off-crest acceleration. The present maximum energy of 14.35 GeV leaves little safety margin to account for klystron failures or shortcomings in klystron performance during operation. It was therefore decided to propose a new maximum for the available linac energy at 14.1 GeV. The required reduction in *K* is discussed below.

Gap Selection

Changes to the undulator gap have much less impact on the overall design and can still be implemented at this stage of the project. In fact, it is possible to design the undulator so that a gap change will be possible after the device is built, by replacing the spacers between the strong back and the magnet/pole array.

Up to now it was assumed, based on the standard Halbach formula for a Nd:FeB Hybrid undulators, that a gap of 6 mm is required to achieve a peak on-axis field value of 1.325 T (or a K value of 3.711) at a period length of 3 cm. With the correction in field strength that is mentioned above, the gap can be opened to 6.35 mm to give the same field value as the 6 mm gap would have given without the field correction. In order to implement the request for a reduction in maximum electron energy to below 14.1 GeV, as discussed above, the gap needs to be opened further to 6.5 mm thus dropping the estimated on-axis peak field to 1.296 T and the K value to 3.630. The 6.5 mm gap height is believed to provide enough space to accept a vacuum chamber with a maximum vertical outer dimension of 6 mm without the undulator being touched. This configuration should allow for the removal of the undulator from the vacuum chamber during operation, as is being considered to help protect the undulator modules from radiation damage during the initial phase of commissioning, without affecting the independently supported vacuum chamber. It is expected that this gap change will cause a very small reduction in peak FEL power.

The undulator modules can be designed so that a change to a different gap height by replacing the spacer blocks, that separate the magnet/pole array from the strong back, will be possible after the devices have been built. Increasing the gap height without changing the electron energy will cause a reduction in resonant FEL wavelength. Pushing the wavelength all the way down to 1 Angstrom at an electron energy below 14.1 GeV will require the gap height to be increased to 8.2 mm. Changing the spacer blocks, after the undulator segments have been installed in the undulator housing, will not be a quick procedure. It will require each undulator to be moved to the magnetic measurement lab for re-shimming and then the reinstallation and realignment of the modules in the undulator housing. Running the FEL with the larger gap undulator modules at 1.5 Angstrom (by reducing the electron beam energy to 11.47 GeV) will reduce the saturation power by about a factor of two and is therefore not desirable for the initial operation of the LCLS at its design wavelength. This reduction in saturation power can be recovered by tapering the last 30-40 m of the undulator, using a new mechanism, proposed by the APS, that allows varying the K values of the undulator modules by about 0.65 %. It has therefore been proposed to not start initially with a gap height of 6.5 mm but instead immediately start with an 8.2 mm gap height. The larger gap will also require reducing the lowest operational energy from 4.5 GeV to 3.6 GeV in order to keep the operational range up to 15 Angstrom. The reduction in energy requires a reduction of the gradients of the quadrupole magnets.

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Reduction in Focusing Strength

The focusing lattice for the LCLS undulator is based on permanent magnet quadrupoles. The focal strength of these quadrupoles has been chosen to maintain an average value of the beta-function at the largest electron energy of 18 m to achieve the shortest saturation length for the FEL. Saturation length and saturation power both depend on the average value of the beta-function. As there is an optimum beta-function value to generate the shortest saturation length, there is also an optimum, but larger, beta-function value for generating the highest saturation power. Both the saturation length as well as the saturation power change faster for small beta-function values than for larger values. At the optimum beta-function value (18 m) for shortest saturation length, the saturation power is about 10 % below optimum. At the optimum beta-function (30 m) for the highest saturation power, the saturation length is only by a few percent reduced. It is now felt that the larger increase in power outweighs the small increase in saturation length and it is therefore proposed to reduce the focal strength of the quadrupoles to increase the average beta-function at 14.1 GeV from 18 m to 30 m.

This reduction in quadrupole strength will ease the situation at the low energy end of the operational range by lowering the lowest energy, that the permanent quadrupole FODO channel will accept, from above 3 GeV to below 2 GeV.

Break Lengths

In the CDR, the general break length pattern is "Short-Short-Long". The break section lengths are designed that the slippage between the electron bunch and the radiation field is either by one or by two optical wavelengths. The pattern can therefore also be written as "1-1-2". The actual lengths were 18.7 cm and 42.1 cm. The first three break lengths are different for reasons of gain optimization. These lengths are too short. It has been decided to increase the break lengths to about 40 cm for the Short and about 60 cm for the Long breaks. With the reduction of the K value from 3.711 to 2.840, due to the gap increase, these lengths can be approximated by a "3-3-4" pattern, which gives the approximate values of about 40.6 cm for the Short and 55.7 cm for the Long break length.

Impact on Beam-Based Alignment

The proposed undulator parameter changes have impact on the beam-based alignment procedure. A recalculation of the new parameters is in progress.

Beam Pipe Radius

Some of the space gain with the gap increase can be used to increase the vacuum chamber from the previous goal values (ID: 5 mm/OD: 5.6 mm). An increase of the inner diameter to 6 mm is conceivable but has not yet been decided.

A summary of the new parameters is given in **Table 1**, which includes the break length increments, i.e., the distances that the separation between two undulator modules needs to be increased to increase the slippage between the electrons and the radiation by one optical wavelength. The increments get smaller as the gap height is increased. Since the actual spacing between undulator modules cannot be changed once the undulator modules are installed, the increase in gap requires the addition of phase adjusters in the gap to correct for the changed phase slip.

Table 1: Undulator Parameters summarizing the proposed changes. The goal for the normalized emittance is 1.2 mm mrad. The supported emittance range goes up to 1.6 mm mrad. The goal values for energy spread ($\sigma_\gamma = 2.8$), and peak current (3400 A) remain unchanged.

Gap height	8.2			mm
λ_r	1.0	1.5	15	Å
E	14.04	11.47	3.63	GeV
γ	27475	22446	7104	
λ_u	3.0	3.0	3.0	cm
B_u	1.014	1.014	1.014	T
K	2.841	2.841	2.841	
Break Incr.	15.11	15.11	15.11	cm
$<\beta_{xy}>$	30	25	10	m
$<\sigma_{xy}>@1.2\ \mu m$	36	37	41	μm

[1] P. Elleaume, J. Chavanne, Bart Faatz, "Design Considerations for a 1 Å SASE Undulator," *NIM A* **455** (2000)