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Multi-pulse effects in the damage to the LCLS reflective optics

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Abstract

A number of experiments to be performed on the planned Linac Coherent Light Source (LCLS) will have to use various types of reflective optics (see, e.g., [1]). On the other hand, LCLS will operate at a rate of 120 x-ray pulses per second. Therefore, when considering effects leading to the damage to its optics, one has to be concerned not only with a possible damage within one pulse, but also with effects accumulating during many pulses. We identify and analyze two of such effects: a thermal fatigue, and the intensity-dependent radiation damage.

The first effect is associated with thermal stresses and deformations that occur in every pulse. The heating of the surface layers of the optics leads to a peculiar distribution of stresses, with a strong concentration near the surface. The quasistatic analysis of this problem was presented in [2]. In the present study, we show that transients in both transverse and longitudinal acoustic perturbations play a significant role and generally worsen the situation. If the maximum stresses approach the yield strength, the thermal fatigue causes degradation of the surface within a few thousands pulses.

The second effect is related to formation of clusters of ionized atoms which lead to gross deformation of the lattice and formation of numerous vacancies and interstitials. At maximum LCLS fluxes, the number of displacements per atom may reach values exceeding unity during a few hours of operation of LCLS, meaning degradation of reflective properties of the surface of the optics. We derive constraints on the admissible fluence per pulse and suggest ways for decreasing the impact of the multi-pulse effects.

1. Introduction

A number of experiments to be performed on the planned Linac Coherent Light Source (LCLS) will have to use various types of reflective optics (see, e.g., [1]). On the other hand, LCLS will operate at a rate of 120 x-ray pulses per second. Therefore, when considering effects leading to the damage to its optics, one has to be concerned not only with a possible damage within one pulse, but also with effects accumulating during many pulses. We identify and analyze two of such effects: a thermal fatigue, and the intensity-dependent radiation damage.

Table I Parameters of the 8-keV LCLS beam [3]

Pulse duration, fs	Total number of photons per pulse, P	Beam radius, r , μm	Beam fluence per pulse, $N_{ph}=P/\pi r^2, \text{cm}^{-2}$	Energy per pulse, E , mJ	Rep. rate, f , Hz
230	$2 \cdot 10^{12}$	60	$1.8 \cdot 10^{16}$	2.6	120

The first effect is associated with thermal stresses and deformations that occur in every pulse. The heating of the surface layers of the optics leads to a peculiar distribution of stresses, with a strong concentration near the surface. The quasistatic analysis of this problem was presented in [2]. In the present study, we show that transients in acoustic perturbations play a significant role and generally worsen the situation. If the maximum

stresses reach the yield strength, the thermal fatigue causes degradation of the surface within a small number of pulses [4].

The damage that has been discussed in Ref. [2] is not caused by the spallation process considered, e.g., in Refs. [5,6]: the spallation threshold is much higher than that obtained in our paper.

The second effect is related to formation of clusters of ionized atoms which lead to gross deformation of the lattice and formation of numerous vacancies and interstitials. As the probability of forming two ionized atoms at a short distance from each other increases as a square of the intensity., the mechanism that we consider is rate-dependent and is specific for very high fluences. We present a preliminary analysis of this mechanism for the parameters of the LCLS beams. At maximum LCLS fluxes, the number of displacements per atom (dpa) may reach values exceeding unity during a few seconds of operation of LCLS, meaning degradation of reflective properties of the surface of the optics.

We derive constraints on the admissible fluence per pulse and suggest ways for decreasing the impact of the multi-pulse effects.

2. Transient effects in thermal stresses

In this section, we consider effects occurring tens of picoseconds and later after the x-ray pulse. At this late stage, the energy delivered by the x-ray beam is thermalized, and a macroscopic description of the deformations and stresses becomes adequate. The concern discussed in Ref. [2] is that these stresses may exceed the yield strength of the material.

We now switch to a discussion of typical spatial and temporal scales of the elasticity theory problem that we are going to consider. For typical materials (e.g., Aluminum and Beryllium), the incident beam at a grazing incidence penetrates the mirror by a distance which is a fraction of a micrometer [5]. The absorption process is dominated by photo-absorption. For 8-keV x rays, the photoelectrons have an energy of ~ 5-6 keV. They deposit their energy at the depth which is typically somewhat greater than photo-absorption depth for a grazing incidence [5,7]. The electron range is between one micrometer and a fraction of a micrometer, depending on the material. So, the initially heated layer will be ~ 1 μm thick [5].

Various characteristic times that we will be referring to, are defined as follows. The sound propagation time over the thickness of the heated layer:

$$t_{s1} = \frac{d}{s_{\parallel}}, \quad (1)$$

where d is the thickness of the heated layer, and $s_{\parallel}$ is the sound velocity for longitudinal acoustic waves; the sound propagation time over the x-ray beam radius,

$$t_{s2} = \frac{r}{s_{\parallel}}, \quad (2)$$

where r is the beam radius; the thermal conduction time over the thickness of the initially heated layer,

$$t_{th} = \frac{d^2}{2\chi} \quad (3)$$

where χ is the thermal diffusivity. Table II contains numerical values of these times for various materials under the assumption that $d=1 \mu\text{m}$, and $r=60 \mu\text{m}$.

TABLE II Characteristic macroscopic times for various materials

	t_{a1} , ns	t_{a2} , ns	T_{th} , ns
Al	0.17	10	5.7
Be	0.08	4.8	9.6

The heating of the surface layer leads to a generation of thermal stresses which may cause degradation of the optical properties of the surface layer within some number of pulses or, in the extreme cases, during a few pulses [4]. One can identify three characteristic phases in the evolution of thermal stresses. The first corresponds to the times shorter than t_{s1} (but, of course longer than a few picoseconds required for the macroscopic description to become valid). The second corresponds to the times comparable to t_{s1} , and the third corresponds to the times much longer than t_{s1} and approaching t_{s2} and t_{th} (The latter two times, as seen from Table II, are comparable to each other).

The stressed state we are dealing with is, generally speaking, not a state of a uni-axial compression or expansion. The stress tensor has several comparable components [2]. In such a case, one can use the Von Mises criterion for the threshold of plastic deformations (see, e.g., [8]), namely that, for the stress tensor reduced to the principal axes, with the principal stresses being $\sigma_1, \sigma_2, \sigma_3$, the onset of plasticity corresponds to

$$\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2] = G^2 \quad (4)$$

where G is a uni-axial yield strength.

During the first stage, the heated layer does not have time to expand, i.e., the strains are still zero, despite the heating. This corresponds to a state of a hydrostatic compression, where the principal values of the stress tensor are all equal [9] and are related to the temperature increase by

$$\sigma_1 = \sigma_2 = \sigma_3 = -\frac{\alpha E \delta T}{3(1 - 2\mu)} \quad (5)$$

where E is the Young modulus, μ is the Poisson ratio, α is the volumetric thermal expansion coefficient, and δT is the temperature increase after the x-ray pulse. At this stage, according to the Von Mises criterion, there is no plastic deformation

At the second stage, the material begins to move in the x direction, because of very large gradients of stresses in this direction, whereas displacements in the y and z directions remain negligible. Finally, at the third stage, the material reaches an elastic equilibrium in the near-surface layer comparable to the beam radius. This stage was considered in Ref. [2].

In this paper we concentrate on the second stage. According to its definition, during the second stage displacement vector has only x component, u_x , and in the strain tensor one can neglect all the components but

$$u_{xx} = \frac{\partial u_x}{\partial x} \quad (6)$$

In this case, the general stress-strain relations yield:

$$\sigma_{xx} = -\frac{\alpha E \delta T}{3(1-2\mu)} + \frac{E(1-\mu)}{(1+\mu)(1-2\mu)} u_{xx} \quad (7)$$

$$\sigma_{yy} = \sigma_{zz} = -\frac{\alpha E \delta T}{3(1-2\mu)} + \frac{E\mu}{(1+\mu)(1-2\mu)} u_{xx} \quad (8)$$

Expressing $\sigma_{yy}(=\sigma_2)$ and $\sigma_{zz}(=\sigma_3)$ in terms of $\sigma_{yy}(=\sigma_2)$, and substituting the result in Eq. (4), one finds the following yield criterion:

$$\frac{1}{1-\mu} \left| \sigma_{xx}(1-2\mu) + \frac{\alpha E \delta T}{3} \right| = G \quad (9)$$

To find the left-hand-side (LHS), one has to solve dynamic equation that takes into account the acceleration/deceleration of the material in the x direction. We can use here the acoustic approximation, because the variation of the density of the material that lead to reaching the yield strength, are in the range of a fraction of a per cent. (Note that in [5] a much higher heating and, accordingly a large variation of the density, exceeding 10%, was considered; the plastic deformations occur actually much earlier, so that there is no need to solve a non-linear problem). For the temperature not varying with time (as in the case that we are considering), the wave equation for the sound wave can be written as:

$$\frac{\partial^2 \sigma_{xx}}{\partial t^2} = s_{\parallel}^2 \frac{\partial^2 \sigma_{xx}}{\partial x^2} \quad (10)$$

with

$$s_{\parallel}^2 = \frac{E(1-\mu)}{(1+\mu)(1-2\mu)\rho} \quad (11)$$

Initial conditions correspond to a zero initial displacement and zero velocity. The first of them can be expressed in terms of σ_{xx} by virtue of Eq. (7) which shows that, at $t=0$, σ_{yy} is determined by Eq. (5). The second initial condition can be formulated in terms of σ_{yy} by differentiating Eq. (7):

$$\frac{\partial \sigma_{xx}}{\partial t} = \frac{E(1-\mu)}{(1+\mu)(1-2\mu)} \frac{\partial u_{xx}}{\partial t} \quad (12)$$

We see that the second initial condition can be presented as $(\partial \sigma_{xx} / \partial t)|_{t=0} = 0$. The boundary conditions are that σ_{xx} vanish at the free surface ($x=0$) and at the infinity. The solution of this problem at $x>0$, $t>0$ is:

$$\sigma_{xx} = -\frac{\alpha E}{6(1-2\mu)} \left[\delta T(x - s_{\parallel} t) + \delta T(x + s_{\parallel} t) - \delta T(-x + s_{\parallel} t) + \delta T(-x - s_{\parallel} t) \right] \quad (13)$$

where the function $\delta T(x)$ is defined as follows: it is the real temperature distribution at $x>0$ and is zero at $x<0$.

Consider, as an example, a step-wise temperature distribution with the width d : $\delta T = \delta T_0$ at $0 < x < d$, and $\delta T = 0$ outside this interval. The stresses at several consecutive moments, as well as the LHS of Eq. (9) at the same moments are shown in Fig. 1. What is important, is that the LHS of Eq. (9) reaches the highest value during the transient stage, at the times $t \sim t_{sl}$. This maximum value is 1.5 times higher than in the steady state that is established at t exceeding a few t_{sl} (this steady state was studied in Ref. [2]). This brings up more stringent conditions for the avoidance of plastic deformations and the thermal fatigue.

Numerical factor that determines the stiffening of the constraints compared to the steady-state analysis depends on the shape of the temperature distribution and may be equal to 1. This happens, in particular, for the linear temperature distribution, $\delta T = \delta T_0(1-x/d)$ at $0 < x < d$, and $\delta T = 0$ outside this interval. For a Gaussian distribution, $\delta T \propto \exp(-x^2/d^2)$, the numerical factor is 1.2. This case is illustrated by Table III. The allowable temperature increase presented in the paper is evaluated from the equation

$$\delta T^* = \frac{3(1-\mu)G}{1.2\alpha E} \quad (14)$$

TABLE III Some thermo-mechanical parameters of aluminum and beryllium

Parameter	Notation and units	Magnitude	
		Al	Be
Volumetric thermal expansion coefficient, $\Delta V/V = \alpha \Delta T$	α , 1/K	$6.9 \cdot 10^{-5}$	$3.15 \cdot 10^{-5}$
Young modulus	E , n/m ²	$6.9 \cdot 10^{10}$	$30 \cdot 10^{10}$
Yield strength*	G , n/m ²	$30 \cdot 10^7$	$150 \cdot 10^7$
Poisson ratio	μ	0.37	0.2
Longitudinal sound speed	$s_{//}$, km/s	6	12.5
Transverse sound speed	$s_{\perp}$, km/s	3	8.8
Density	ρ , g/cm ³	2.7	1.85
Thermal capacity	c_p , J/(cm ³ ·°K)	2.5	3.3
Thermal diffusivity	χ , cm ² /s	0.87	0.52
Melting temperature	T_m , K	930	1560
Allowable temperature increase per pulse	δT^* , K	80	320
Allowable dose, eV/atom	D , eV	0.021	0.053

*The number for aluminum corresponds to an aluminum alloy with 2.2 % of copper and 0.2-0.5 % of chromium.

We see that the onset of plastic deformations corresponds to a very modest dose, well below the dose required for melting (Cf. Ref. []). The density variations produced at the critical temperature increase are small.

The density variation corresponding to the onset of plastic deformation can be found from the general expression $\delta \rho / \rho = -u_{xx}$ by substituting to the RHS an expression for u_{xx} obtained from Eqs. (7) and (9). The result reads:

$$\left| \frac{\delta \rho}{\rho} \right|_{\max} = \frac{(1 + \mu)G}{E} \quad (15)$$

Relative density variations do not exceed 0.6%. This justifies the use of a linear (acoustic) model.

III. Rate-dependent formation of point defects

In this section, we consider a very different damage mechanism that occurs during the x-ray pulse and shortly thereafter. It is related to formation of defects (voids and interstitials) caused by ionization and excitation of the atoms in the crystalline lattice (e.g., [10,11], and references therein). In such a case, because of the change of the atomic configuration, the interaction of the atom with the surrounding atoms changes, creating local deviation from the equilibrium crystal lattice. With some probability, this non-equilibrium state may relax to the state where a point defect is formed, e.g., an interstitial. The probability of this event is relatively low, because the interaction potential of an excited or ionized atom with surrounding neutral atoms is relatively small, in the range of 1 eV, even for the closest neighbors situated at the inter-atomic distance a .

Had *two* ionized atoms been formed at a distance of even $(2-3)a$, their interaction potential would be substantially larger, in the range of a few eV. This high repelling potential would cause formation of defects with a high probability, ~ 1 . However, at the “normal” fluences formation of close pairs of ionized atoms occurs with a negligible probability, because an ionized state recombines much quicker than a closed ionized neighbor can be formed. and this process does not play any significant role.

The situation changes dramatically at extremely high intensities characteristic of LCLS. As the pulse is shorter than or comparable to the recombination time of an ionized atom and, on the other hand, the fluence is very high, there is a substantial probability that *two* ions will be formed at a distance comparable to a . In this case, the interaction potential is substantially higher, in the range of 10 eV. If this happens, then, with a probability approaching 100%, the two ions will blow-up the lattice in their and form point defects. In fact, more than one dpa may occur per one close ion pair, but we will be working under the most optimistic assumption that only one dpa occurs.

In what follows, we provide a qualitative, phenomenological description of this process. We consider materials with moderate-to-low atomic number, from beryllium to silicon, and photon energies in the range of 8 keV characteristic of the LCLS facility. In this case, the absorption occurs predominantly via the ionization (see, e.g., Ref. [5] and references therein). As the photon energy greatly exceeds the ionization potential, the initially formed electrons produce a number of secondary ionizations. We shall characterize this phenomenon by a number K of the ionizations per the initial photon; K is typically in the range of several hundreds. (Cf. detailed calculations for diamond, for lower energy electrons, presented in Refs. 10-11).

The number density of the atoms is related to the atomic weight A and the mass density ρ of the material by

$$n = \rho / A m_p. \quad (16)$$

For a rough preliminary estimates, we will ignore the details of the crystal structure and characterize the medium just by the average inter-atom distance

$$a = n^{-1/3}. \quad (17)$$

We designate the photon fluence (number of photons per unit area normal to the beam direction) as N_{ph} , and the attenuation coefficient (an inverse e-folding length of the beam) by μ .

The number of absorption events occurring per unit volume during the pulse is μN_{ph} . An average distance between the absorption points is

$$a_{abs} = (\mu N_{ph})^{-1/3} \quad (18)$$

An energetic electron formed in such a point causes secondary ionizations in its vicinity [10, 11]. The primary electron experiences scattering, so that the area where secondary ionizations occur can be roughly characterized as a sphere of a radius l_i of order of a fraction of a range of the primary electron. According to Refs. 5-7, this distance for 6-7 keV electrons is ~ 0.5 - $1 \mu\text{m}$. We assume that a_{abs} is less than l_i . In this case, the ionizations from the neighboring absorption points overlap, forming a quasi-homogeneous distribution of the ionized atoms. As we will see shortly, the condition

$$l_i < a_{abs} \quad (19)$$

indeed holds. The number density of ions formed per unit volume after the passage of the x-ray pulse is then, obviously,

$$n_i = K\mu N_{ph} \quad (20)$$

We neglect here the recombination, which is justifiable for the LCLS pulse length. These ions are randomly distributed over the volume. The average distance between the ions is

$$a_i = n_i^{-1/3} = (K\mu N_{ph})^{-1/3} \quad (21)$$

One can note in passing that, in the case opposite to (19), i.e., at low fluence per pulse, secondary ionizations occur in separate clusters around the absorption points (Fig. 2). The ionization density inside the clusters is less than the estimate (20) by a factor $(a_{abs}/l_i)^3$.

We are interested in the ion pairs situated at the distance less than a certain number C of the inter-atomic distances a :

$$l = Ca \quad (22)$$

with C being equal to 3-4. Note that the distance l is much less than the typical Debye radius for silicon and diamond (Cf. Ref. 10-11), so that the interaction between the ions in a close pair occurs without screening. Beryllium is a highly conducting metal and screening in it may play a role. For now, however, we ignore this effect and just caution that the screening may change our predictions.

With the interaction energy of a few electron-volts, the time within which the ions and surrounding atoms will move around is of order of the inter-particle distance a divided by the velocity corresponding to the interaction energy. The latter is $\sim 10^6 \text{ cm/s}$, so that for the size of the zone involved $\sim 10^{-7} \text{ cm}$, the characteristic time will be $\sim 100 \text{ fs}$, i.e., shorter than recombination time.

According to the previous discussion, if two ions appear at the distance less than l , point defects (interstitials and voids) are formed, whereas for the pairs formed at larger distances the interaction energy is too small to produce defects. The close pairs constitute a small fraction β of the total number of ions; this fraction is, obviously,

$$\beta = n_i l^3 = n_i C^3 a^3 = C^3 \frac{n_i}{n} \quad (23)$$

The total number of point defects formed per unit volume of the material per one pulse is βn_i . [We remind of our assumption that only one displaced atom is formed by every close ion couple; in reality, more than one defect can be formed.] The fraction ε of the displaced atoms compared to the total number of atoms is

$$\varepsilon = \beta \frac{n_i}{n} = C^3 \left(\frac{K \mu N_{ph}}{n} \right)^2 \quad (24)$$

Table IV represents numerical values of various parameters for beryllium and silicon.

Table IV. Rate-dependent formation of the defects for the 8-keV beam*

	ρ , g/cm ³	n , cm ⁻³	$a=n^{-1/3}$, cm	μ , cm ⁻¹	a_{abs} , cm	a_i , cm	ε
Si	2.33	$5 \cdot 10^{22}$	$2,7 \cdot 10^{-8}$	143	$0,7 \cdot 10^{-6}$	$1,2 \cdot 10^{-7}$	$1,05 \cdot 10^{-3}$ (C=2)
C (Diamond)	3.5	$1,75 \cdot 10^{23}$	$1,8 \cdot 10^{-8}$	15.3	$1,5 \cdot 10^{-6}$	$2,5 \cdot 10^{-7}$	$3,3 \cdot 10^{-6}$ (C=3)
Be**	1.85	$1,2 \cdot 10^{23}$	$2 \cdot 10^{-8}$	1.9	$3 \cdot 10^{-6}$	$5,1 \cdot 10^{-7}$	$1,08 \cdot 10^{-7}$ (C=3)

* All the derived parameters are obtained for the fluence of $N_{ph} = 2 \cdot 10^{16}$ cm⁻² and $K=200$.

** Beryllium is a metal where the screening may reduce the repulsion effect.

The results obtained mean that, within 10^3 pulses (~ 10 seconds of LCLS operation) every atom in the silicon optics will be displaced from its initial position. For the diamond, the same will occur within less than an hour.

4. Discussion

We have considered two mechanisms that may lead to a degradation of the LCLS optics within some number of pulses, ranging from a few thousands to several millions (which correspond to a few seconds to a few hours of the LCLS operation). One of the mechanisms is a thermal fatigue, which leads to a gradual cracking and the loss of smoothness of the surface of the reflective, grazing incidence optics. This mechanism works on the time-scale of order of a nanosecond. The limiting fluence depends on the thermal expansion coefficient and the material strength. The best performance can be expected from beryllium.

The second mechanism is of a non-thermal nature and acts during the pulse and immediately after it, before the recombination of the ionized atoms occurs. We have identified key parameters determining such a damage and can, in particular, expect that beryllium will be much more resilient than silicon or carbon. We also note that even for beryllium the rough estimate of the number of pulses within which dpa becomes ~ 1 corresponds to only a few hours of the LCLS operation. We emphasize that this result was obtained under an optimistic assumption that the close ion pair forms only one displaced atom. Although we have primarily concentrated on the reflective optics, this second mechanism works also for transmission optics, e.g., zone plates.

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References

- [1] A. Wootton, J. Arthur, T.Barbee, R.Bionta, A.Jankowski, R. London, D. Ryutov, R. Shepherd , V. Shlyaptsev, R.Tatchyn, A.Toor. Nuclear Instruments & Methods in Physics Research Section A-Accelerators Spectrometers Detectors & Associated Equipment. **483**, 345, 2002.
- [2] D.D. Ryutov. Rev. Sci. Instr., **74**, 3722 (2003).
- [3] The LCLS Design Study Group. *Linac Coherent Light Source (LCLS) Design Study Report* , Report SLAC-R-521, Stanford University, 1998.
- [4] A. Weronski, T. Hejwowski. *Thermal fatigue of metals* (Marcel Dekker, Inc., New-York – Basel – Hon Kong), p.110, 1991.
- [5] R.A. London, R.M. Bionta, R.O. Tatchyn, S. Roesler. “*Computational Simulations of High-Intensity X-Ray Matter Interaction*” In: Proceedings of SPIE (R.O. Tatchyn, A.K. Freund, T. Matsushita – Eds), v. 4500, p. 51 (2001).
- [6] S. Eliezer, E. Moshe, D. Eliezer. Laser & Particle Beams. **20**, 87 (2002)
- [7] L.V. Spencer. Phys. Rev., **98**, 1597 (1955).
- [8] A. Mendelson. *Plasticity: Theory and Application*. (Krieger Publ., Malabar, 1968).
- [9] L.D. Landau and E.M.Lifshitz. *Theory of Elasticity* (NY, Pergamon Press, 1986).
- [10] Ziaja B. Szoke A. van der Spoel D. Hajdu J. Physical Review B. 6602(2):4116, 2002.
- [11] Ziaja B. van der Spoel D. Szoke A. Hajdu J. Physical Review B. 6421(21):4104-+, 2001.

Fig. 1 Stresses produced by the step-wise temperature distribution (shaded). The x -coordinate is normalized to the initial width d ; the stress is normalized to $(1-\mu)\alpha E\delta T_0/3(1-2\mu)$. The pictures correspond to $t=0$, $d/4s_{||}$, $d/2s_{||}$, $3d/4s_{||}$, $d/s_{||}$ and $t \gg d/s_{||}$. L.h.s. of Eq. (9) is shown by a thick line. Later in time, the bi-polar acoustic pulse formed at $t=d/s_{||}$ moves to the right (and outside the picture), without further change of the shape. It leaves behind a static thermal stress analysed in Ref. 2. Note that, at the intermediate times, the L.h.s. of Eq. (9) is 1.5 times higher than at the later static stage, meaning that plastic deformations occur at a lower temperature.

Fig. 2. Absorption process at low (a) and high (b) intensities. In the first case the distance a_{abs} between absorption points is much greater than the radius of the ionization cluster l_i . In the second case, with the same radius of the cluster, the distance between their centers becomes small, and the clusters overlap.