

Thermal damage at short electron bunches passage through a thin target

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Abstract. The thin target could be used for beam diagnostics by means the radiation that is induced by interaction of beam particles with target matter. The electron beams used in modern applications (as, for example, modern FELs) have very large brightness, small emittance as well as very short bunch length. For example, the bunch length of XFEL is about of 25 μm at bunch charge order of 1 nC and with electrons energy of 17.5 GeV. The passage of this powerful short bunches could damage the target or even completely destroy it. In the presented work the train of such bunches passages through the target is investigated. It is shown the target works in extreme regime close to phase transition temperature.

1. Introduction

Intense ultrashort soft and hard X-ray pulses will give rise to new opportunities for studies in time-resolved spectroscopy, diffraction, and imaging. These pulses can be generated from free-electron lasers (FELs) such as FLASH (DESY, Germany) [1], LCLS (SLAC, USA) [2], SACLA (Spring-8, Japan) [3], or the European XFEL (DESY, Germany) [4]. A key requirement in realizing an accelerator like an x-ray FELs is a high brightness electron beam that possesses a high peak current, i.e. a high bunch charge (typically few nC) compressed to an extremely small longitudinal extension (few tens μm), and a very low transverse emittance. The diagnostics of the electron bunch length which typically is the order of few tens of fs is of crucial importance. The information on the bunch shape could be obtained by the analysis of the radiation that is generated in the solid target placed in the beamline [5,6].

The applicability of beam diagnostics schemes that use the radiation in solid targets at FELs parameters demands the additional investigations. The interaction of the short powerful bunches with a solid medium leads to fast and significant local heating in the small volume of target. From one hand, the target could be overheated because the train typically consists of few thousands of bunches. Hence, one should be sure the local temperature in the interaction area does not exceed the critical temperature (for example, the phase transition temperature). Moreover, the radiation properties also could change because the medium parameters depends on the temperature. From the other hand, the fast heating in the small area generates the mechanical stress waves spreading over the target. The stress oscillations could also damage the target even if there is not overheating.

This work is devoted to the investigation of the target heating at FELs electron beam parameters. Namely, the passage of short electron bunches through the thin diamond target is considered. The beam parameters assumed below are: electron energy $E = 17.5$ GeV, bunch



charge $q_0 = 4$ nC, bunch length RMS $l = 25$ um, bunch transverse dimension RMS $\sigma = 10$ um, the time between bunch passages is $\Delta t = 100$ ns [4]. The angular divergence is negligible for the task. The target is the thin round plate with thickness $h = 10$ um and radius $R = 5.6$ mm. In simulations the critical temperature is $T_{cr} = 2273$ K when the phase transition takes place, and the target is broken due to the overheating. The beam heats the center of the target along its axis, see in figure 1.

In the work firstly the applicability of heat conductivity theory is verified at conditions of the task. Than the simulations are carried out to estimate possible thermal damage of the target as well as to find the safe regime of the beam passage.

2. Theoretical model

When the train of electron bunches passages through the solid target the particles interact with the medium, and they loss their energy. The energy can be transferred to the medium (ionization loss) or can be radiated (radiation loss). In this work the radiation absorption in the medium is neglected so the target heating is caused by the ionization loss. Initially the projectiles transfer their energy to electrons of the medium. After that this energy spreads to the ionic lattice of target while the temperature of electronic and ionic components of the medium do not became equal. The characteristic time of relaxation is $t_r \sim 0.1$ ns. Hence, the heat spreading over the medium can not be considered by using the usual conduction theory at the time range $t \leq t_r$.

Assuming the Gaussian longitudinal density of bunch electrons, the estimation of bunch length is $6l$. Hence, the bunch passage time, when energy is transferred to the target, is $t \approx (h + 6l)/c = 0.53$ ps (c is the speed of light, it is approximately equal to the velocity of beam's electron). So, $t \ll t_r \ll \Delta t$. Hence, the beam interaction with the target could be considered at two steps. At the first step the energy transfer could be considered instantaneous, whereas at the second step the heat spreading between bunch passages should be considered based on the heat conductivity theory.

The ionization loss $|-dE/dx| = 4.76$ MeV/cm for one 17.5 GeV electron was evaluated by using the GEANT4 toolkit [7]. The bunch contains q_0/e electrons. Hence, at the bunch passage the target gets the heat $Q_b = |-dE/dx|q_0h/e = 19.04$ uJ (e is the electron charge). For the Gaussian beam considered here the electron flux at the distance r from the target axis depends on the time t as

$$n(r, t) = n_0 \exp \left[-r^2/(2\sigma^2) \right] \exp \left[-(ct)^2/(2l^2) \right].$$

The electron number that passage through the thin ring layer with the radius r , thickness dr , and coaxial with the target is

$$dn(r) = \int_{-\infty}^{\infty} n(r, t) dt \cdot 2\pi r dr = \frac{(2\pi)^{3/2} n_0}{c} l r \exp \left[-r^2/(2\sigma^2) \right] dr, \quad (1)$$

where $2\pi r dr$ is the thin layer cross-section. The constant n_0 is defined by the condition on the total number of electrons in the bunch:

$$\int_0^{\infty} dn(r) = \frac{q_0}{e}, \text{ therefore, } n_0 = \frac{q_0 c}{(2\pi)^{3/2} e l \sigma^2}. \quad (2)$$

Substitution of equation (2) in equation (1) gives

$$dn(r) = \frac{q_0}{e \sigma^2} r \exp \left[-r^2/(2\sigma^2) \right] dr.$$

During the bunch passage the thin layer gets heat

$$dQ = Q_b \frac{e}{q_0} dn(r) = \frac{Q_b}{\sigma^2} r \exp \left[-r^2/(2\sigma^2) \right] dr.$$

The thin layer volume is $dV = 2\pi r h dr$. Therefore, the instantaneous jump of temperature depends on the distance r to target axis and is defined by the expression

$$\Delta T(r) = \frac{dQ}{\rho c_p dV} = \frac{Q_b}{2\pi \rho c_p h \sigma^2} \exp \left[-r^2 / (2\sigma^2) \right],$$

where ρ is the target density, and c_p is the target heat capacity. In particular, the maximal temperature jump (evaluated at initial temperature $T_0 = 300$ K) is $\Delta T(0) = 1724$ K and it takes place at the target axis. It should be noticed here the simulations are carried out within the wide temperature range. So, both the density and the heat capacity should be considered as temperature dependent functions at the moment when the bunch hits the target.

The temperature spreading over the target between bunches (during the time Δt) is described by the equation:

$$\frac{\partial T}{\partial t} = a \left[\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) + \frac{\partial^2 T}{\partial x^2} \right],$$

where a is the thermal diffusivity of the target material. The target is considered to be placed in the vacuum and anchored at lateral cylindrical surface (see in figure 1). So, the boundary conditions for both beam entrance and exit round surfaces were black body radiation with the ambient temperature T_0 :

$$\left(\frac{\partial T}{\partial x} \right)_{\text{entrance, } x=-h/2} = -\epsilon \sigma_{SB} \left(T^4(-h/2, r, t) - T_0^4 \right),$$

$$\left(\frac{\partial T}{\partial x} \right)_{\text{exit, } x=h/2} = \epsilon \sigma_{SB} \left(T^4(h/2, r, t) - T_0^4 \right),$$

where ϵ is the surface emissivity and σ_{SB} is the Stefan Boltzmann constant. The temperature of the lateral surface was fixed at T_0 . The same temperature $T_0 = 300$ K is the initial temperature for whole task.

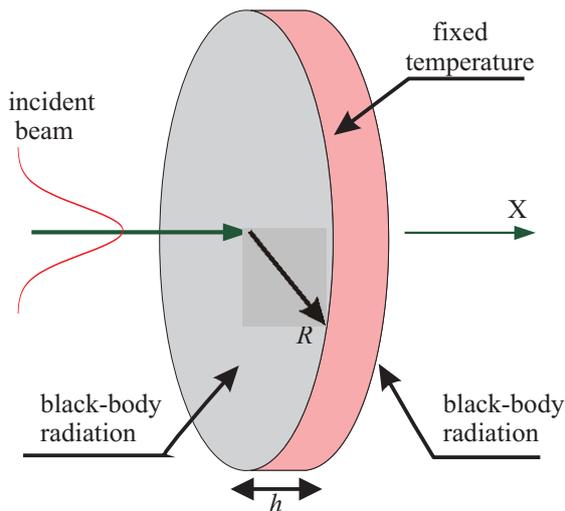


Figure 1. The geometry of the model and boundary conditions. The beam hits the target along target axis denoted by X .

3. COMSOL simulations and discussion

The model developed above was simulated by COMSOL Multifysics software [8]. Target parameters were taken from COMSOL database (namely, C diamond [solid, thin film] was used

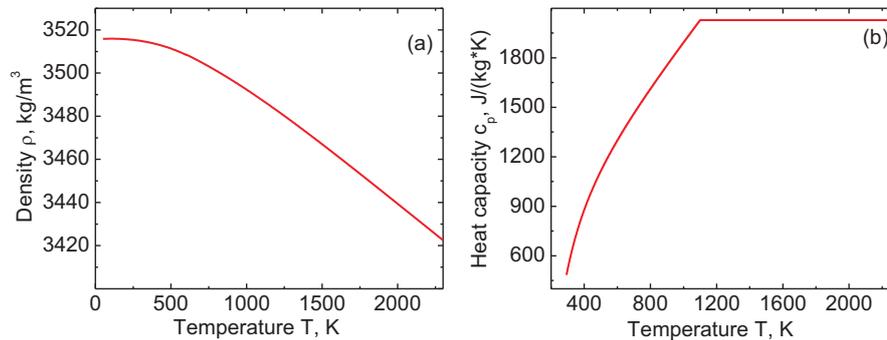


Figure 2. COMSOL data. Dependencies on the temperature T : (a) the material density $\rho(T)$, (b) the material heat capacity $c_p(T)$.

as material) taking into account their temperature dependencies (see in figure 2). The diamond thermal conductivity $k = 2000 \text{ W}/(\text{m}\cdot\text{K})$ ($a^2 = k/(\rho c_p)$) as well as surface emissivity $\epsilon = 1$ were introduced manually. The maximal temperature during the train passage is suspected at the target axis. The corresponding temperature evolution is shown in figure 3. Here one can see both the temperature jumps when a bunch hits the target and the relaxation between bunches. It should be noticed the first bunch at $t = 0$ produces the maximal temperature jump. After that jumps are drastic reduced due to the increasing of heat capacity as shown in figure 2(b). These jumps have close values because the material parameters change slightly in the temperature range where simulations are carried out. The relaxation stages between bunches produce close values of temperature decreasing, about of 400 K, excepting the first relaxation stage when the temperature falls down at 600 K. The detailed data are presented in table 1. As the matter of fact the temperature decreasing during relaxation stages become bigger with every successive stage (starting from the second relaxation stage) due to the spreading of the heat from the central area of the target to its periphery. In principle, the temperature decreasing at the relaxation would be equal to the temperature jump for the large enough bunch numbers. But the simulations show the target will be broken at 11-th bunch passage. Usually train consists of several thousands of bunches. So, the application of thin target at FELs beam diagnostics is obstructed.

To make the heat spreading over the target more clear several samples of the temperature distribution along the target radius are shown in figure 4. The area shown in the figure includes the range of $0 \leq r \leq 8\sigma$ where the beam hits the crystal and where the heat spreads while the target keeps undamaged. The difference between curves 1 and 2 demonstrates the temperature jump when the second bunch hits the target (see in figure 3). One can see the jump depends on the distance from the crystal axis. The curve 3 demonstrates the temperature at the finish of the second relaxation stage. The comparison of curves 2 and 3 illustrates the heat flux in the target during one relaxation stage. Heat transfers from the central area of the target so the temperature increases at the periphery of the shown area whereas the temperature decreases near the axis. The curve 4 shows the temperature in the middle of the last relaxation stage. One can see the temperature at the distance $r > 8\sigma$ remains practically equal to initial temperature T_0 . This means the additional cooling of the lateral surface can not protect the target because $R \gg \sigma$, and the target is overheated in its central area before the heat flux can reach the target lateral edge.

The simulations show the target is overheated at modern FELs electron beams with the bunch charge order of 1 nC. In principle, there would be possible the stable regime when

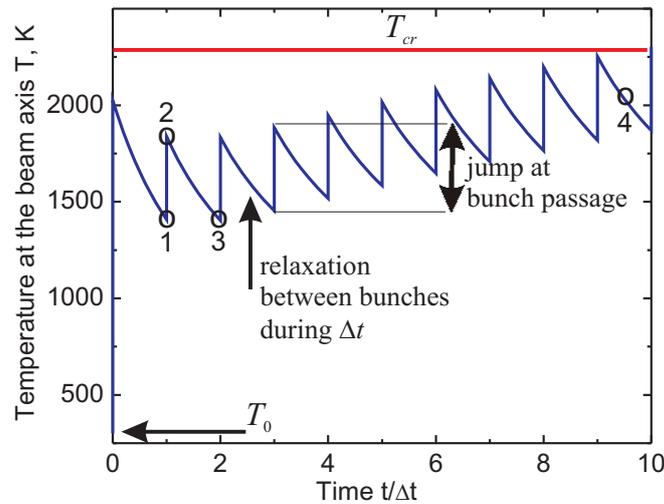


Figure 3. Temperature at the target axis when train of electron bunches passages through the target. The initial target temperature is $T_0 = 300$ K, the critical temperature of phase transition is $T_{cr} = 2273$ K. The target is overheated after 11-th bunch. Open circles denote corresponding curves in figure 4.

Table 1. Data on the beam passage through the target which is shown in figure 3.

Bunch number	Temperature jump at the bunch passage, K	Initial temperature at relaxation, K	Temperature decreasing at relaxation, K	Final temperature at relaxation, K
1	1724	2024	616	1408
2	435	1838	435	1403
3	430	1833	380	1453
4	431	1884	367	1517
5	431	1948	364	1584
6	431	2015	367	1648
7	431	2079	371	1708
8	432	2140	375	1765
9	433	2198	379	1819
10	433	2252	382	1870
11	433	2303	-	-

the temperature jump at the bunch passage equals to temperature decreasing at successive relaxation. More realistic, at the large time limit the difference between target temperatures at the finish of two successive bunch passages should tend to zero.

The drastic way to find the safe regime for target is to decrease the bunch charge q_0 . The simulation of the whole train by using the COMSOL is not possible due to technical restrictions. To estimate the target temperature after the 1000 bunches the next method was used. The passage of 19 bunches with the charge q_0 was simulated. After that the difference of temperatures δT after 18-th and 19-th bunches at the target axis was evaluated. The corresponding value for

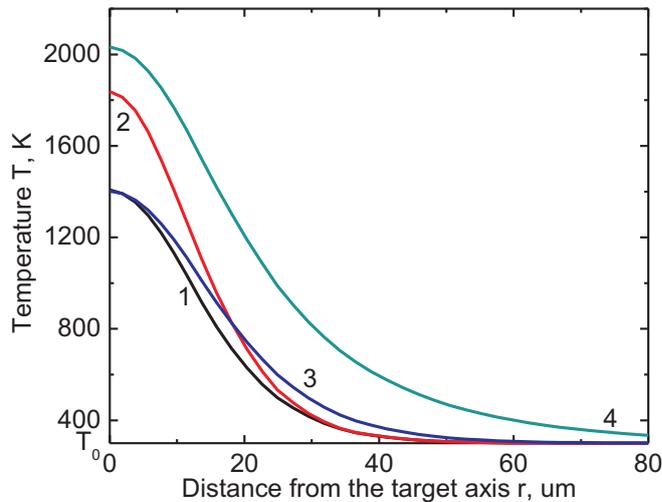


Figure 4. Dependencies of temperature on the distance from the target axis at different time moments: 1 — the finish of the first relaxation stage, 2 — the finish of the second bunch passage, 3 — the finish of the second relaxation stage, 4 — the middle moment of the tenth relaxation stage (see in figure 3).

Table 2. The top estimation T_{est} of the target temperature after the train passage in dependence on bunch charge q_0 .

q_0 , nC	T_{est} , K	Comparison with T_{cr}	Result
1.0	8300	$\gg T_{cr}$	Crash
0.5	5300	$\gg T_{cr}$	Crash
0.25	2300	$\sim T_{cr}$	Danger
0.1	1370	$< T_{cr}$	Safe

next bunches (after 19-th bunch) should be less than δT so the value $T_{est} = T_0 + 1000\delta T$ gives the rough top estimation of the maximal target temperature after the whole train passage. If this estimation gives $T_{est} \gg T_{cr}$ one could surely say the target will be broken, if $T_{est} \sim T_{cr}$ there is the danger of overheating, if $T_{est} \ll T_{cr}$ the regime of the train passage is safe. These estimations for different values of q_0 is given in table 2. One can see the target could not be damaged if the bunch charge would be about of 0.1 nC, i.e. one order less than the FELs bunch charge that we are interested here.

4. Conclusion

In this paper the heating of thin target was investigated when it is irradiated by the train of short powerful electron bunches. The electron beam properties, in general, corresponds to parameters of modern FELs facilities. The overheating of the target was demonstrated clearly. It was shown the bunch charge should be significantly reduced to avoid the thermal damage of the target.

Finally, it should be underlined the target heating depends strongly on both bunch charge and material properties that define the temperature jumps at bunch passages. Moreover, the large temperature jumps concentrated in the small central area of the target should lead to the appearance of mechanical stress waves in the target. This stress can be additional cause of the target both damage and breakage. This problem needs additional investigation in view of solid target application for the beam diagnostics.

Acknowledgments

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