WAKEFIELDS IN THE SUPERCONDUCTING RF CAVITIES OF LCLS-II*

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INTRODUCTION

The superconducting cavities in the linacs of LCLS-II are designed to operate at 2K, where cooling costs are high. In addition to an unavoidable static load and the dynamic load of the fundamental 1.3 GHz accelerating RF, a further heat source is the higher order mode (HOM) power deposited by the beam. The layout of LCLS-II is sketched in Fig. 1. In L3, the final linac, due to the extremely short bunch length, the beam spectrum extends well above cut-off into the terahertz regime. Ceramic absorbers, at 70K and located between cryomodules (CMs), are meant to absorb much of this power. However, understanding their effectiveness is a challenging research topic.

In this report we primarily calculate the amount of power that the beam radiates in the three linacs of LCLS-II, L1, L2, L3, and in the linearizing, 3rd harmonic (3.9 GHz) cavities. To do this we find the steady-state wakes as well as the transients at the beginning of the three linacs. At the ends of each linac there is a matched pair of 1 cm to 3.5 cm (radius) step transitions, whose effect is also considered. Finally, we estimate—under the pessimistic assumption that all the wake power ends up in the SRF walls—the wall heating and the extent of Cooper pair breaking in L3, where the bunch is most intense. Note that all calculations here are of single bunch effects; resonant interactions are not considered.

In our calculations we assume for LCLS II 1.2 MW of beam power, with charge q = 300 pC and repetition rate f_{rep} = 1 MHz. The bunch shape is nearly Gaussian in L1, L2, and uniform in L3, with rms bunch length σ_z = 1000, 270, 25 μm in the three linacs [1]. Note that the charge represents the maximum charge to be used: nominally q= 100 pC and σ_z = 8 μm (in L3). More details of this report can be found in [2]. A theoretical study of exactly where the HOM power will be absorbed is given in [3].

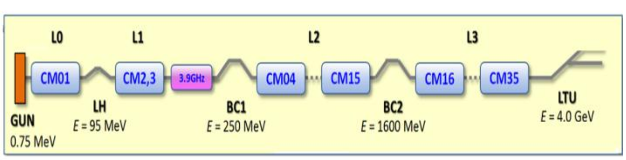

Figure 1: Schematic layout of LCLS II linac which contains the laser gun; acceleration sections L0-L3 having 1.3 GHz TESLA-type CMs (CM01-CM35) and 3.9 GHz CM; laser heater (LH); two bunch compressors (BC1-BC2), and Linac-to-Undulator transfer line (LTU).

WAKEFIELD LOSSES IN CMS

A TESLA CM comprises eight 9-cell cavities, each with active length 1.036 m and iris radius a = 3.5 cm. Between the cavities are bellows that are roughly 6 cm long and have 11 oscillations. When the beam enters the first CM in a linac, it will first encounter transient wakefields that will gradually change to the steady-state wakes. The change occurs over a distance on the order of the catch-up distance, $z_{cu} = a^2/2\sigma_z$. For LCLS-II, the catch-up distance z_{cu} = 0.6, 2.3, 25 m in the 3 three linacs. For all three linacs z_{cu} is small compared to the length of the sequence of CM, meaning that the steady-state results are a good approximation to the average CM wakes. However, the transient wakes excited in the first cavities of each linac are stronger than the steady-state ones, and need to be considered separately.

Steady-State Wakes

The wake power lost by the beam in a CM is given by $P_{wake} = q^2\kappa f_{rep}$, with κ the loss factor per CM. For a sufficiently short bunch, κ—for any cylindrically symmetric, periodic structure with minimum radius a—can be approximated by the asymptotic value (see *e.g.* discussion in [4])

$$\kappa = \frac{Z_0 c L}{2\pi a^2} \qquad (1)$$

with Z_0 = 377 Ω, c the speed of light, and L the structure length. From this formula (taking $L = L_c$ = 8.3 m, a = 3.5 cm) we estimate the steady-state power radiated per CM, P_{asym} = 11 W. We perform a more accurate calculation taking as point charge wake the approximation [5]

$$W(s) = 344.\, e^{-\sqrt{s/s_0}} \quad \left[\frac{V}{pC\cdot CM}\right] \qquad (2)$$

with s_0=1.74 mm, which includes the effects of the cavities, the bellows, and pipes in between. The loss factor for a Gaussian bunch is given by

$$\kappa = \frac{1}{2\sqrt{\pi}\sigma_z}\int_0^\infty W(s) e^{-\frac{(s/\sigma_z)^2}{4}} ds \qquad (3)$$

Performing the integral (3) using this wake (2), we find that κ= 86, 119, 154 V/pC, or P_{wake} = 7.7, 10.7, 13.8 W, in L1, L2 and L3. Note that for a uniform bunch distribution, as is found in L3, if we take σ_z to represent the rms length, the loss factor will differ, but only by a small amount.

Transient Wakes

When a short bunch enters the first cell of the first cavity in a linac, the wake induced will be well approximated by the diffraction model [6], and in subsequent cells and cavities the wake will gradually reach its steady-state form. Let us begin by considering the bunch at its shortest, in L3, where σ_z = 25 μm. According to the diffraction model, the loss factor for a

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Gaussian bunch passing through the first cell of a cavity is given by [6]

$$\kappa = 0.723\frac{Z_0 c}{\sqrt{2}\pi^2 a}\sqrt{\frac{g}{\sigma_z}} \quad (4)$$

with g the cell gap. For the TESLA CM, the cell period p = 11.5 cm, and the gap can be taken to be g = 8.9 cm. Using Eq. 4, we find that κ = 10 V/pC is the contribution for the first cell; for the first cavity, the diffraction model would give this value multiplied by the number of cells in a cavity: $\bar{\kappa}$ = 90 V/pC (the bar over κ indicates loss per cavity).

To estimate the loss in CM n, κ_n, we consider the model

$$\kappa_n = \sum_{m=1}^{8}\bar{\kappa}_{nm} = \frac{1}{9}\sum_{m=1}^{8}\sum_{p=1}^{9}[\bar{\kappa}_{tr}e^{-\alpha_{nmp}} + \bar{\kappa}_{ss}(1-e^{-\alpha_{nmp}})] \quad (5)$$

with m the cavity number and p the cell number; with $\bar{\kappa}_{tr}, \bar{\kappa}_{ss}$, respectively the transient and steady-state per-cavity loss factor; with $\alpha_{nmp}=[72(n-1)+9(m-1)+p-1]/9d_c$, where d_c is the declination, per cavity, of the transient component. In Ref [7] the changing per cavity loss factor is calculated for a σ_z = 50 µm bunch as it passes through one TESLA CM. Calculations made according to the model (5) with $\bar{\kappa}_{tr}$ = 63.6 V/pC, $\bar{\kappa}_{ss}$= 17.0 V/pC, and d_c = 1.25 fit the numerical calculations well [2]. The transient loss factor $\bar{\kappa}_{tr}$ is given by the diffraction formula (4), $\bar{\kappa}_{ss}$ is taken from Ref. [7]—it agrees well with the steady-state wake formula used in the previous section. Note that the declination d_c is equivalent to a distance of 1.25 m, which is much less than the catch-up distance, z_{cu} = 12 m, the distance after which the wake experienced by the beam is within a few percent of the steady-state wake (see e.g. Ref. [8]).

We repeat the calculation for the case of L3 in LCLS-II, where σ_z = 25 µm, taking $\bar{\kappa}_{tr}$= 90 V/pC (from the diffraction model), $\bar{\kappa}_{ss}$= 19 V/pC (from the steady-state section above), and d_c = 2.5 (since the bunch has half the length of the previous case). We obtain the result that κ=327, 161, 154, 154 V/pC, or P_{wake}= 29.5, 14.5, 13.8, 13.8 W in the first 4 CMs of L3. For completeness, we repeated the calculations for the beam passing through the initial CMs of L1 and L2. We find that in L1 the loss in the first CM is 7.8 W, and the result for all the others is 7.7 W; in L2 the loss in the first CM is 11.1 W, and the result for all the others is 10.7 W.

End Transitions

There are matched pairs of 1 cm to 3.5 cm transitions at the ends of L1, L2, and L3. One can use the optical model of wakefields to estimate the power radiated due to these transitions. One obtains *e.g.* that 46 W is radiated at the ends of L3. However, this transient effect interferes with the transient effect at the first CM discussed above. With more study, we finally estimate that the extra radiated power due to the end transitions is reduced from 46 W to less than 10 W; and this total amount is distributed over the first and last 50 m of L3. (See [2] for more details.)

THE 3.9 GHz CRYOMODULES

Two 3.9 GHz SRF CMs will be installed upstream of BC1 for longitudinal phase space control. The total length of each is 12 m. Each CM comprises eight 9-cell cavities, each of which has active length L_{cav}=34.6 cm; the cavity-to-cavity spacing is 1.38 m. The iris radius a=1.5 cm. Many details of the CM layout have not yet been decided on. Rather than attempt a simulation of the wake at this point, we will just make an estimate of the power generated by the beam passing through the 3.9 GHz CM. I. Zagorodnov et al have performed detailed calculations for the 3.9 GHz CM to be used in X-FEL [9]. The X-FEL 3.9~GHz CM has the same cavity shape as will be used in LCLS-II. However, each 3.9 GHz CM of X-FEL has only 4 cavities (plus bellows and end transitions).The authors find that, for a σ_z=1 mm bunch, κ=71 V/(pC·CM). For an estimate for LCLS-II, with its 8 cavities per CM, we simply multiply their result by two: *i.e.* we let κ=142 V/pC. Then, the power radiated by the beam in each CM is ~13 W. The reason this number is not large compared to what we found in L3 of the main linac is that here the bunch is relatively long and the cryomodule is relatively short. In the future, when the LCLS-II CM layout is set, numerical simulations should be performed to confirm this estimate.

PULSED TEMPERATURE RISE CAUSED BY THE BUNCH FIELDS

The effects we consider in this and following sections are most pronounced when the beam has high peak current, and since the bunches have the highest peak current in L3, from here forward we will limit ourselves to considering only the L3 CMs; all the analysed effects will only be weaker in L1 and L2. In L3 the bunch shape is approximately uniform, the bunch time duration $\tau=2\sqrt{3}\sigma_z/c$ = 290 fs, and thus the instantaneous current during a pulse is $I_p = q/\tau$ = 1 kA, which produces magnetic field of the amplitude $H = I_p/(2\pi a)\approx$ 4.6 kA/m on the surface of the aperture. Since the bunch time duration is smaller than electron-phonon relaxation time, there is no effective Meissner screening and this will lead to the instantaneous dissipation power of about $P_d \approx \rho H^2/(2l)$ where ρ ~ 1 nΩm is the normal state electrical resistivity at 2K, and l ~1 µm is an electron mean free path in high RRR niobium. We obtain $P_d \approx$ 1 W/cm^2 during time of order τ leading to the energy deposition per unit volume of $\Delta W/\Delta V = P_d\tau/l$ = 3.1 nJ/cm^3. Taking the specific heat of superconducting Nb at 2K [10] to be c_{heat} = 0.12 mJ/(cm^3·K), we obtain for the pulse heating $\Delta T_{pulse} = (\Delta W/\Delta V)/c_{heat} \leq$ 0.025 mK.

AVERAGE TEMPERATURE RISE CAUSED BY THE BUNCH FIELDS

The time-averaged dissipated power is $P_d\tau f_{rep}\approx$ 3.1 mW/m^2. Taking a niobium wall thickness of 3 mm, the thermal conductivity and Kapitza resistance from [11], and solving for the steady state heat diffusion, we find that there will be a negligible temperature increase on the cavity wall (near the aperture), $\Delta T_{avg} \approx 0.004$ mK. Thus, neither thermal quench nor extra dissipation – due to non-equilibrium Meissner screening around the apertures - are issues. If we take the affected area to be of width d ~1 cm around each aperture, this will lead, for a 9-cell cavity with 10 apertures, to a deposited energy of about $10\times P_d 2\pi a d\tau \approx 0.07$ nJ per bunch, or an additional time-averaged power of $P_{davg} = 0.07$ mW << P_{diss}=13 W (Table 1). It is important to note that the lack of Meissner screening of the magnetic field for the ultrafast bunch is purely a non-equilibrium, relaxation effect which does not directly affect the superconducting surface resistance and thus the dissipation in the fundamental mode. An additional dissipation in the beam pipe of length ~ 13 cm will be $P_d 2\pi a\tau f_{rep}\times 13$ cm= 0.08 mW, which is small compared to the thermal flow from the beam pipe and coupler, ~ 0.12-0.16 W (for the end cavities).

COOPER PAIR BREAKING BY THz RADIATION

The additional power P_{wake} will increase wall losses in the fundamental mode due to two effects: an increase in RF surface temperature ΔT, and an increase in the fraction of unpaired electrons Δn_N. An estimate of ΔT using the same parameters as above gives $\Delta T \approx 1$ mK, and a corresponding additional dissipated power $P_1 \approx 0.1$ W << P_{diss}. To estimate the extent of the breaking of Cooper pairs in the niobium by the fields of the beam, we calculate the wakefield power for frequencies above the pair breaking threshold frequency, $f_{cpb} = 750$ GHz. When the beam traverses the beginning of L3, the high frequency impedance is one that can be approximated by the diffraction model; eventually, the high frequency impedance of a periodic structure applies. Of the two models, the diffraction model power drops more slowly at high frequencies, so it is in the first cavities of L3 that the breaking of Cooper pairs will be largest in number. The relative power radiated above the Cooper pair breaking threshold can be approximated by

$$r_{cpb} = \frac{1}{2\pi\kappa}\int_{f_{cpb}}^{\infty} R(\omega) e^{-\left(\frac{\omega\sigma_z}{c}\right)^2} d\omega \qquad (6)$$

with $R(\omega)$ the real part of the impedance and ω the frequency. For the transient wake we use the diffraction model [6] and obtain $r_{cpb} = 0.33$. For the steady-state wake we use the periodic diffraction model of Gluckstern [12, 13]. At high frequencies $R(\omega)$ for this model drops as $\omega^{-3/2}$, which is faster than the $\omega^{-1/2}$ dependence for the diffraction model. For the steady-state wake $r_{cpb} = 0.01$ [2]. The total number of Cooper pairs in the magnetic field penetration depth δ ~ 100 nm (where photon absorption happens) of one 9-cell cavity with surface area $S_A = 0.8$ m^2 at 2K is given by [14]

$$N_{Cooper} \cong \frac{\Delta E}{E_f} n_e S_A \delta \qquad (7)$$

with the band gap of niobium $\Delta E = 1.55\times10^{-3}$ V, the Fermi energy $E_f = 5.35$ V; where the density of normal conducting electrons $n_e = \rho Z/(A m_p)$, with niobium density $\rho = 8.57\times10^5$ kg/m^3, atomic number $Z = 41$, atomic weight $A = 93$, and proton mass $m_p = 1.672\times10^{-27}$ kg. We find that $\Delta E/E_f = 2.9\times10^{-4}$, $n_e = 2.3\times10^{30}$ m^{-3}, and finally $N_{Cooper} = 5\times10^{19}$. Converting the total wakefield energy deposited per bunch into number of $f \geq 750$ GHz photons (in a cavity; remember there are 8 cavities in a CM) we obtain:

$$N_{ph} = \frac{1}{8}\frac{r_{cpb} U_{wake}}{h f_{cpb}}, \qquad (8)$$

with $h = 6.63\times10^{-34}$ J·s, Planck's constant. We find that, for the transient (steady-state) case, $N_{ph} = 5.4$ (0.04) $\times10^{15}$, which in both cases is negligible compared to N_{Cooper}. Thus pair-breaking induced by both the increase in normal fluid density and in the surface resistance are negligible. Since the characteristic electron-phonon relaxation time $\tau_{e\text{-}ph}$ is on the order 400 fs, by the time the next bunch arrives in 1 µs, the number of Cooper pairs is back to thermal equilibrium, and no cumulative effects occur.

CONCLUSION

In this note we calculated the power radiated by the beam that can end up in the CMs of LCLS-II. We considered the worst case scenario of charge $q = 300$ pC and repetition rate $f_{rep} = 1$ MHz. From the RF cavities themselves, the steady-state loss is 8, 11, 14 W per CM in the three linacs; the loss in the first CM of L3, however, is a transient that is estimated to be 30 W. For the radiation generated in the symmetric pair of 1 cm to 3.5 cm (radius) transitions at the ends of L3, we estimate an additional contribution of 10 W (in total). Meanwhile, for the 3.9 GHz CMs, 13 W is radiated per CM.

Since the power lost by the beam $P_{wake} = q^2\kappa f_{rep}$, the power radiated by the nominal $q = 100$ pC bunch will be much reduced compared to these numbers. In L3 the steady-state (transient) losses in the CMs becomes 1.5 (5.6) W. We also estimated, for the high charge case, the heating and Cooper pair breaking due to the wake and conclude that these effects are small—even under the pessimistic assumption that all the radiated power is absorbed in the cavities.

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