

# Generation and Absorption of the Untrapped Wakefield Radiation in the 3.9 GHz LCLS-II Cryomodule

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#### **1 ABSTRACT**

Construction of the Linac Coherent Light Source II (LCLS-II) is underway for the world's first hard Xray free-electron laser. A central part of the LCLS-II project is a 4 GeV superconducting radio frequency (SCRF) electron linac that will operate in continuous wave (CW) mode. The linac is segmented into four sections named as L0, L1, L2 and L3. The 3.9 GHz third harmonic cavities will be used in the section L1 of the linac for linearizing the longitudinal beam profile [1]. Cavities are primary sources of a beam excitation of broadband wakefield, which cannot be extracted effectively using higher order mode couplers, and therefore, most of the associated power is deposited to cryomodules and beam line components. Evaluation of power deposition by untrapped radiation is critical for determination of the overall cryogenic heat load and preventing an overheating of beam line components. In this paper, we present numerical and analytical evaluations of wakefield electromagnetic spectrum in the 3.9 GHz cryomodule. Furthermore, a detailed analysis is performed in order to estimate power depositions in the third harmonic section of the LCLS-II linac using diffusion and transition models.

#### **2 INTRODUCTION**

A continuous wave operation regime of the 3.9 GHz LCSL-II accelerating structure at maximum average beam current of 0.3 mA and 1 MHz bunch repetition rate is resulted in about ten watts of uncoherent RF losses in the form of untrapped high-order-modes (HOM) propagating along the beam line. The electromagnetic spectrum of wakefield is limited by the length of a single bunch, which is 1 mm rms in the L1 section of the linac. Therefore, the bandwidth of wakefield, carried over 99% of total radiated power, is about 100 GHz in the L1 section comparing to 1 THz broadband wakefield in the L3 section, where the bunch length is 25  $\mu$ m [2]. Comparison of electromagnetic spectrums of two wakefields is presented in Figure 1. We discuss the details of wakefield electromagnetic spectrum simulations in the section 3 bellow.



Figure 1 Spectrum of electromagnetic power of wakefields in 3.9 GHz (red) and 1.3 GHz (blue) cryomodules of L1 and L3 linac sections respectively.

A thorough analysis of wakefield power deposition in the 1.3 GHz LCLS-II cryomodule is presented first in [3], where most of the power (>80%) is predicted to be absorbed in the special ceramic absorber installed between cryomodules. This initial estimation is based on the diffusion model of a photon gas and it does not count radiation losses. Later the model was improved by adding auxiliary beam line components and a semi-analytical approach of a wakefield radiation to fundamental and high-order-modes couplers, but the overall balance of power depositions has a minor change [4]. In a contrary, the wakefield in the 3.9 GHz cavity has a denser low frequencies spectrum and propagates in the beam line with smaller aperture. Hence, we may expect larger couplings of propagating HOMs with external ports of the cryomodule. For an accurate calculation of wakefield heat loads in the 3.9 GHz cryomodule, we introduce two new methods: a) wakefield expansion into propagating modes in the circular beam pipe, where to the initial approximation we count that all modes are monopole only. Consequently, in the transition model we use direct numerical calculations of multimode s-matrixes for an estimation of the wakefield power absorption (radiation) in individual beam line

components. The method of equivalent surface impedances comes straightforward as the result of wakefield decomposition and implies a substitution of the individual component by a section of circular pipe with an equivalent surface impedance providing the same single pass wakefield power loss. We apply then equivalent impedances for simulation of heat loads balance using the diffusion model.

#### **3 WAKEFIELD ELECTROMAGNETIC SPECTRUM SIMULATIONS.**

For an axially symmetric structure and a bunch with charge q(s) moving along the axis the electromagnetic power spectral density of a wakefield is defined as a convolution of the longitudinal impedance with the bunch density [5]:

$$\frac{dP}{d\omega} = q_0^2 f_b Z_{\parallel}(\omega) e^{-\left(\frac{\omega\sigma_z}{c}\right)^2} \tag{1}$$

where  $q_0$  is the bunch charge,  $f_b$  is the bunch repetition rate,  $Z_1$  is the cryomodule impedance and  $\sigma_z$  is the bunch rms length. The longitudinal impedance is determined as a Fourier harmonic of the point wake function:

$$Z_{\parallel}(\omega) = \frac{1}{\pi c} Re(\int_0^\infty w_{\parallel}^0(s) e^{-\frac{i\omega s}{c}} ds)$$
<sup>(2)</sup>

For the first time simulations of wake fields in the third harmonic section of the TTF-II facility is presented in [6], where authors describe the analytical expression of the wake function by fitting it with numerically obtained wake potential. We follow to a similar procedure for finding wake function of the 3.9 GHz LCLS-II cryomodule. The detailed layout of the cryomodule is shown in Figure 2. Each cryomodule contains eight cavities, nine bellows with flanges and two gate valves. There is a transition section with increased 78 mm aperture between cryomodules, where the beam line absorber (BLA) is installed. The results of loss-factor calculations using ECHO 2D program are summarized in the Table 1 [7].

Table 1 Loss-factors of the 3.9 GHz cryomodule and sub-components

Input geometry	Loss-factor, [V/pC]	
Cavities only	113.9	
Cavities and bellows	135.5	
Full 3.9 GHz CM	151.6	



Figure 2 Beam line layout of the 3.9 GHz cryomodule for the LCLS-II linac

Based on ECHO results we derived analytical approximation for the point longitudinal wake function:

$$w_{\parallel}^{0}(s) = -H(s) \left( A e^{-\sqrt{s/s_{0}}} + 0.9 \frac{\cos(5830s^{0.83})}{\sqrt{s} + 195s} + B\delta(s) \right), [V/pC]$$
(3)

where H(s) and  $\delta(s)$  are Heaviside step function and Dirac delta function,  $s_0 = 8.4*10^{-4}$ , A = 784, B = 1098. Comparison of wake functions of 1.3 GHz and 3.9 GHz cryomodules are illustrated in Figure 3. Numerical coefficients in the formula (3) are chosen for best fit with the ECHO wake potential simulation.



Figure 3 Longitudinal wake function of a point like charge in 1.3 GHz (blue) and 3.9 GHz (red) cryomodules

For a single bunch of charge Q passing through the cavity parallel to the axis, the wake potential is given by the convolution of the wake function with the bunch density:

$$W_{\parallel}^{0}(s) = \frac{1}{q} \int_{-\infty}^{s} w_{\parallel}^{0}(s - s')q(s')ds'$$
<sup>(4)</sup>

$$q(s) = \frac{1}{\sqrt{2\pi\sigma_z}} e^{-\frac{s^2}{2\sigma_z}}$$
(5)

The result of an approximation of the numerical (ECHO) wake potential in the 3.9 GHz cryomodule by the analytical equation (4) is presented in Figure 4 for the Gaussian bunch of 1 mm rms length.



Figure 4 Comparison of ECHO 2D (solid blue) and analytical (dotted red) wake potential in the 3.9 GHz LCLS-II cryomodule

Finally, we obtain the steady state power density of the wakefield for an rms bunch length of 1 mm; a bunch charge 300 pC and a 1 MHz bunch repetition rate (see Figure 1). Since we are interested in a study of power deposition by untrapped HOMs only, we excluded the part of the wakefield spectrum below the beam pipe cut off frequency of the first propagating monopole mode. The integrated steady state wakefield power

is presented in Figure 5 for 1.3 GHz and 3.9 GHz LCLS-II cryomodules. The overall powers of wakefields above the  $TM_{01}$  mode cut off are estimated to be 12.8 W and 9.4 W respectively.



Figure 5 Integrated steady state wakefield power generated by 25 µm bunch (blue) and 1 mm bunch (red) of 300 pC and 1 MHz, in the 1.3 GHz and 3.9 GHz LCLS-II cryomodules respectively.

#### **4 TRANSITION MODEL**

The wakefield transition model is based on the idea of a wakefield decomposition into propagating modes in the circular beam pipe, which is the analogue of Fourier basis [8]. Since the full-scale 3D analysis of a propagation of all circular waveguide modes is too complex and time consuming, we simplify the problem by taking into account only monopole  $TM_{0n}$  modes exited by a beam and neglecting further transformations to non-symmetrical modes. Besides, the  $TM_{0n}$  modes are mixed by themselves during a propagation through the cryomodule. Numerical results of the ANSYS HFSS [9] analysis of monopole modes transmission through the 3.9 GHz cavity at high frequency range is presented in Figure 6.





One can see that a single monopole mode at the input is almost equally mixed up with others propagating  $TM_{0n}$  modes after a transmission through the cavity. Thus, as the initial approximation we can assume that wakefield power is equally distributed among all propagating  $TM_{0n}$  mode at the given frequency:

$$P_{wake}(\omega) = \sum_{n=1}^{N(\omega)} \frac{P_{-TM_{0n}}}{N(\omega)}$$
(6)

where  $N(\omega)$  is the number of TM<sub>0n</sub> modes below the cut off at given frequency. The composition of the integrated wakefield power in the 3.9 GHz cryomodule is shown in Figure 7 for the first three monopole modes. Finally, we can estimate the single pass absorption of the wakefield power in the individual beam

line components:

$$P_{abs} \approx \sum_{n=1}^{N} \int_{\omega c_{01}}^{\infty} \frac{dP_{TM_{0n}}}{d\omega} (1 - S_{12}^2 - S_{11}^2) d\omega$$
(7)

where  $\omega c_{01}$  is the cut off frequency of the first propagating TM<sub>01</sub> mode,  $dP_{TM0n}/d\omega$  is the TM<sub>0n</sub> mode power density of the decomposed wakefield,  $S_{12}$  and  $S_{11}$  are transmission and reflection elements of scattering matrix of the TM<sub>0n</sub> mode at the given frequency.



Figure 7 Monopole modes composition of the integrated wakefield power in the 3.9 GHz cryomodule

The results of ANSYS HFSS driven modal simulations are presented in Figures 8 and 9 for monopole modes transmission through the BLA and the fundamental power coupler (FPC). The FPC model includes a ceramic window and a copper antenna. The BLA in LCLS-II cryomodules contains a hollow ring of the lossy STL-150D aluminum nitride ceramic by Sienna Technology [10, 11]. According to the vendor specification, the ceramic has a measured permittivity  $Re(\varepsilon)/\varepsilon_0 < 30$  and a loss tangent  $\delta > 0.4$  in the frequency range of 5 GHz to 12 GHz. As a conservative approach we take constant values of  $Re(\varepsilon)/\varepsilon_0 = 30$  and  $\delta = 0.4$  for ceramic broadband properties up to 100 GHz.





Figure 8 Electrical field distribution for BLA (left) and FPC (right) components of the 3.9 GHz cryomodule with the TM<sub>01</sub> mode excitation at 20 GHz frequency.



Figure 9 Transmission of TMon modes through the BLA (left) and FPC (right) beam line components

We performed similar calculations of scattering matrices for all beam line components in the thirdharmonic section of the LCLS-II linac, including radiations to gate valves, HOM couplers and to the upstream warm section of the beam pipe with reduced 32 mm aperture. Evidently each components is characterized by a maximal coefficient of a power absorption (radiation) of the  $TM_{0n}$  signal near the cut off frequency and it further gradual decay toward the high frequency range. The final estimation of single pass wakefield power losses in individual beam line component is summarized in the Table 2.

Component	BLA	FPC	Gate Valve	НОМС	Bellows (Cu-plated)	End Pipe (2.5 m, SS)	End Pipe (Ø32 mm, rad.)
1-pass loss, [%]	42	20	2.7	1.6	0.2	11	41

Table 2 Single pass wakefield power losses in beam line components of the 3.9 GHz section

In our particular interest, we can calculate the amount of wakefield power radiated upstream and downstream from the cryomodule. For a rough approximation, we assume that wakefields are radiated symmetrically by each cavity in the cryomodule and the cavity itself does not introduce any losses and reflections. Before the wakefield reaches the cryomodule exit, it propagates through the chain of cavities, couplers and bellows. Hence, the power radiated to each side by a single 3.9 GHz cryomodule is defined:

$$PCM_{rad} \approx \frac{P_0}{16} \sum_{i=1}^{8} \left( 1 - (SP_{FPC} + 2 \times SP_{HOM} + SP_{BELLOWS}) \right)^i = 1.7 \ [W] \tag{8}$$

where  $P_0 = 9.4$  W is the total integrated wakefield power of the cryomodule and  $SP_{FPC}$ ,  $SP_{HOM}$ ,  $SP_{BELLOWS}$  are a single pass signal power loss in couplers and bellows. Taking into account multiple signal reflections from cavities it is likely that the coupling with external ports is increased and, hence, less wakefield power will be radiated outside of the cryomodule.

#### 5. DIFFUSION MODEL

The diffusion model was proposed for the estimation of an absorption of the wakefield generated by ultra-short bunches in the 1.3 GHz XFEL cryomodule [3, 12]. There are two approaches used in the diffusion model: a) the wakefield energy is uniformly distributed and fully absorbed within the periodic section of the linac and b) wakefield power deposition is proportional to the overall surface areas occupied by the beam line component and its surface impedance. While the diffusion model is a good approximation for the broadband wakefield in the 1.3 GHz cryomodule, we have to use it carefully in the 3.9 GHz cryomodule, where an electromagnetic spectrum of the radiated wakefield is much narrower and a wakefield coupling with external ports is large (see Table 2).





An important parameter of the diffusion model is the surface impedance. There is a straightforward definition of a surface impedance for lossy conductors as the real part of the surface resistance:

$$Z_S = Re(R_s(1+i)) = \sqrt{\frac{\omega\mu_0}{2\sigma}}$$
(9)

where  $\sigma$  is the material conductivity. In addition, we have to introduce the model of equivalent impedances for losses associated with power radiations or absorptions within beam line components for an adequate use of the diffusion mode. The idea is a substitution of a lossy element by the section of a beam pipe with an equivalent surface impedance and a length corresponding to the same amount of a power loss due to wakefield propagation. Numerically calculated spectrums of wakefield losses in the beam line components of the 3.9 GHz cryomodule are illustrated in Figure 10. Following to the wakefield decomposition method described in (6), the single pass power loss of the n<sup>th</sup> monopole mode at given frequency is equal to:

$$dP_n(\omega) = P_0(1 - e^{-2\alpha}n^l)$$
(10)

where  $l = S_{rad}/(2\pi r_b)$  is the length of a section,  $S_{rad}$  is the area of a lossy element occupied in the beam pipe,  $r_b$  is the beam pipe radius and  $\alpha$  is the attenuation constant. For monopole modes, the attenuation constant is defined as:

$$\alpha_n(\omega) = \frac{Z(\omega)}{Z_0 r} \left( \sqrt{1 - \left(\frac{\omega c_n}{\omega}\right)^2} \right)^{-1}$$
(11)

where  $Z(\omega)$  is the equivalent impedance at given frequency and  $Z_0$  is the free space impedance. Finally, we can sum up losses from each monopole mode and equal it to the result of a direct numerical simulation:

$$dP(\omega) = \sum_{n=1}^{N(\omega)} dP_n(\omega)$$
<sup>(12)</sup>



Figure 11 Equivalent surface impedances (dotted) of beam line components and impedances of the stainless still 316L and copper materials.

By solving the system of nonlinear equations (12), we can derive equivalent surface impedances for all beam line components. The result is shown in Figure 11 with a comparison to impedances of the stainless steel 316L used for some components and the copper within assumptions of the anomalous skin effect (ASE) and a low value of the RRR = 15 [13]. One can see that the equivalent impedance of the BLA is about twice larger than the theoretical value for a lossy ceramic given in [3]. The difference is explained by the nature of the BLA design, where electromagnetic field penetrates into the hollow ceramic ring on both inner and outer sides (see Figure 8), while the theoretical result takes only the inner ceramic surface into account.

Table 3 List of beam line components in the 3<sup>rd</sup> harmonic section of the LCLS-II linac

Component	BLA	FPC	Gate Valve	НОМС	Bellows (Cu-plated)	End Pipe (2.5 m, SS)	Spool Pipe (1 m, Cu)
#	2(3)	16	4	32	18	1	1
Surface area, [mm <sup>2</sup> ]	1.4e4	7.1e2	2.0e2	3.1e2	3.7e4	6.2e5	1.0e5

The list of beam line components and their surfaces are provided in the Table 3 as an input for the diffusion model analysis of wakefield power depositions in the 3<sup>rd</sup> harmonic section of the LCLS-II linac.

## 6. WAKEFIELD POWER DEPOSITONS ANALYSIS

The layout of the 3rd harmonic section of the LCLS-II linac is shown in Figure 12 for two considering options: a) a single BLA is installed after the CM1 3.9 GHz cryomodule and b) two BLAs are installed after both CM1 and CM2 cryomodules. The left side BLA belongs to the preceding 1.3 GHz cryomodule, but we included it to our model since it absorbs a major part of the upstream wakefield radiation.



# Figure 12 Proposed layouts of the 3<sup>rd</sup> harmonic section of the LCLS-II linac with one (A) and two (B) beam line absorbers installed after 3.9 GHz cryomodules

For a calculation of wakefield power deposition, we count only first two passes of the signal transmission in the transition model and we neglect any signal radiation out of the 3<sup>rd</sup> harmonic section in the diffusion model. The results of a wakefield power deposition analysis are summarized in the Table 4.

	Wakefield Power Deposition, [W]						
Component	Transitio	on Model	Diffusion Model				
	А	В	А	В			
BLA	2.6	3.6	10	12			
Bellows (Cu&SS)	0.14	0.14	0.16	0.12			
Spool Pipe (Cu)	0.01	0.01	0.01	0.01			
End Pipe (SS)	0.3	0.16	0.8	0.6			
FPC	11.6	11.5	5.7	4.5			
НОМС	1.8	1.7	0.8	0.6			
Gate Valve	0.6	0.55	1.4	1.1			
Downstream Radiation	0.9	0.3	-	-			
Upstream Radiation	0.9	0.9	-	-			
Total Power	18.9	18.9	18.9	18.9			

Table 4 Wakefield power depositions in the 3 <sup>rd</sup> harmonic section of the LCLS	5-II linac	С
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Evidently, a significant amount of the wakefield power is radiated to FPC and HOMC ports. According to the transition model over 65% of wakefield power is absorbed within the 3.9 GHz cryomodule itself. Installation of an additional BLA (variant B) looks impractical since it intercepts only 5% of the total power. For a conservative estimation, we assume that all radiated power is absorbed within beam line components.

The final list of cryogenic heat loads caused by a wakefield radiation in the 3<sup>rd</sup> harmonic section of the LCLS-II linac is presented in Table 5 for the baseline variant A. Both models predict similar heat loads on 2K and 50K cooling circuits, while the transition model estimates more accurately the radiation to HOM couplers resulting in about 1.8 W heat load to the 5K cryogenic line.

Wakefield Radiation	Cryogenic Heat Loads, [W]				
Model	2 K	5 K	50 K		
Transition	0.14	1.8	16.1		
Diffusion	0.16	0.8	17.9		

Table 5 Cryogenic heat loads in the 3rd harmonic section of the LCLS-II linac

# 7. CONCLUSIONS

The estimation of wakefield power deposition in the 3<sup>rd</sup> harmonic section of the LCLS-II linac is completed using two independent transition and diffusion models. Both models show a significant amount of radiated wakefields, up to 65%, going to FPC and HOMC ports of the 3.9 GHz cryomodule. Thus, the major part of the total wakefield power (85%) is a source for the 50 K cryogenic heat load, while the rest is resulted in about 10% and 1% of the power deposition going to 5 K and 2 K circuits respectively.

### 8. REFERENCES

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