HOMs and Wakes in LCLS–II Superconducting Linac

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Introduction

- It is costly to remove power deposited at 2K (or 4K) in linac cryomodules (CMs). In LCLS-II, HOM's generated by the beam will add to the power load, especially in the last linac (L3), where the peak current is highest
- Ceramic absorbers, located between CMs and tied to 70K are meant to absorb the HOM power.
- In this talk I will focus on calculations of wake power, lost by the beam, that may end up in the CMs. I will also present some new calculations on how much of that power is absorbed at 2 or 4K

Much of what I present can be found in K. Bane, A. Romanenko, V. Yakovlev, LCLS-II TN-13-04 (2013). Transient wake and spectrum calculations were done with G. Stupakov. S-matrix results performed with C. Adolphsen and C. Nantista.

Note: Eu X-FEL project has long ago covered much of this topic—see M. Dohlus 2007 talk on web

Outline

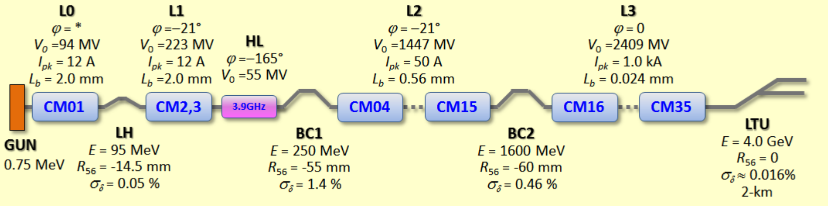
HOM Power Loss

- Main linac cavity wakes: steady state and transient
- HOM spectrum generated by beam
- Effect of 1 cm to 3.9 cm (radius) beam pipe transitions at ends of L3
- 3rd harmonic cavity
- Coherent synchrotron radiation (CSR) from bunch compressors

Power Deposition

- S-matrix calculations

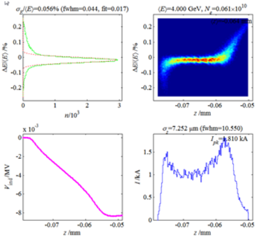
LCLS-II - Linac and Compressor Layout for 4 GeV



100-pC machine layout: Oct. 8, 2013; v21 ASTRA run; Bunch length L_b is FWHM

Linac Sec.	V (MV)	φ (deg)	Acc. Grad. (MV/m)	No. Cryo Mod's	No. Avail. Cav's	Spare Cav's	Cavities per Amplifier
L0	94	*	13.2	1	8	1	1
L1	220	–21	14.1	2	16	1	1
HL	–55	–165	14.5	3	12	1	12
L2	1447	–21	15.5	12	96	6	32
L3	2409	0	15.4	20	160	10	32

Includes 2-km RW-wake



* L0 cav. phases: ~(3.4°, -15.2°, 0, 0, 0, 15°, 15°), with cav-2 at 22% of other L0 cavity gradients.

(P. Emma)

Steady-state wake

Table : LCLS-II parameters used in our calculations (for L3). The longitudinal bunch distribution is approximately uniform. Note that in L1, L2, the bunch distribution is approximately Gaussian, with rms bunch length $\sigma_z = 1$, 0.25 mm, respectively.

Parameter name	Value	Unit
Charge per bunch, Q	300	pC
Rms bunch length, σ_z	25	μm
Cavity aperture, a	3.5	cm
Repetition rate, f_{rep}	1	MHz

• The HOM power generated by the beam is $P = Q^2 \varkappa_\lambda f_{rep}$. The nominal bunch charge in LCLS-II, $Q = 100$ pC; however, the combination $Q = 300$ pC, $f_{rep} = 1$ MHz, will generate the highest HOM power in LCLS-II

Steady-state wake

- Weiland and Zagorodnov have computed the short-bunch wake in a TESLA cryomodule (with bellows), and fit their results to $W(s) = 344.e^{-\sqrt{s/s_0}}$ [V/(pC*CM)] with $s_0 = 1.74$ mm (TESLA Report 2003-19; see also report by A. Novokhatski)

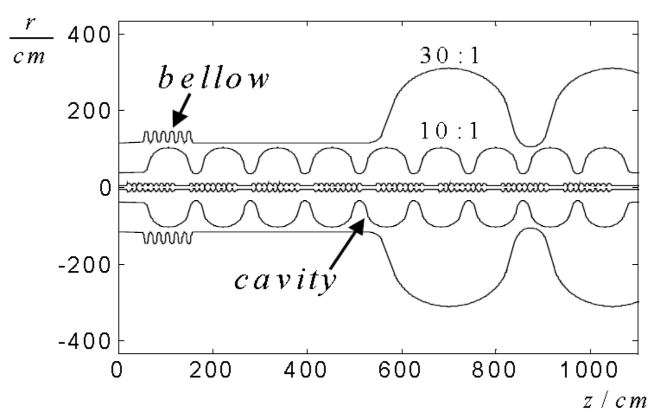


Figure : TESLA geometry. A CM comprises 8 nine-cell cavities (from Weiland and Zagorodnov)

Steady-state losses

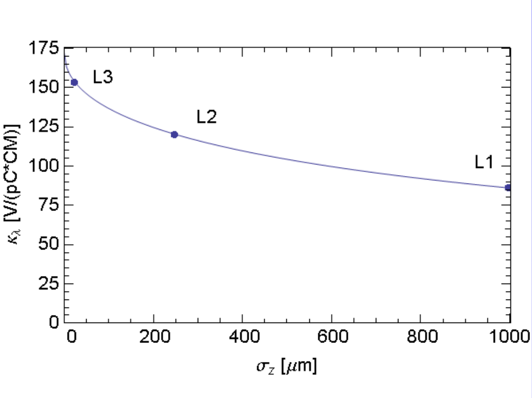


Figure : For Gaussian bunch and analytic steady-state wake, $\varkappa_\lambda$ *vs.* σ_z. The bunch lengths in the three linacs of LCLS-II are indicated by the plotting symbols

- The beam ($Q = 300$ pC, $f_{rep} = 1$ MHz) loses 7.7, 10.7, 13.8 W/CM in L1, L2, L3 (except for first two CM)

Spectrum of Power Loss in L3

- The steady-state power spectrum is obtained by Fourier transforming the steady-state wake.

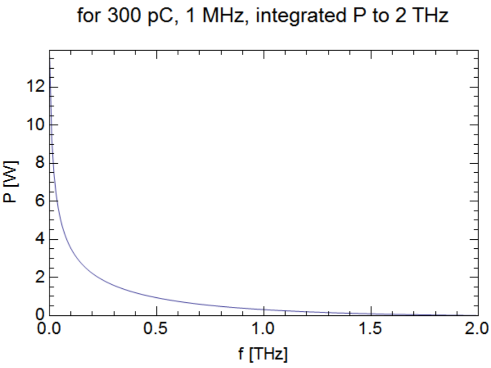


Figure : Integrated spectrum of power loss in the L3 cryomodules, but not the first one. Total power lost by beam is 13.8 W. About 50% of the power is above 20 GHz, 25% above 100 GHz. Rms bunch length $\sigma_z = 25\ \mu\text{m}$

Transient Wake

- For a short bunch passing through a periodic structure, it takes on the order of the catch-up distance, $z_{cu} = a^2/2\sigma_z$, to reach the steady-state wake. For L3 taking $a = 3.5$ cm (cavity iris radius) and $\sigma_z = 25$ μm, $z_{cu} = 25$ m

- When the beam enters the first CM of L3, the first cell loss factor is given by the diffraction model ($\varkappa_\lambda \sim \sigma_z^{-1/2}$), and each cell wake becomes more like the steady state wake. In this manner, one can compose a transient model for the beginning of L3 by summing a geometric series (see LCLS-II TN-13-04).

- In the first four CMs of L3 we find that 29.5, 14.5, 13.8, 13.8 W is lost by the beam

- Direct calculation of the transient wake using a time-domain program like Echo is difficult to do because of the huge number of mesh points involved. However, G. Stupakov has obtained the transient wake with Echo using scaling (see his talk)

Transient Wake Cont'd

- The transient spectrum (for the first cryomodule) obtained by Fourier transforming G. Stupakov's transient wake. As we see, the spectrum extends about twice as far as before, to ~ 4 THz

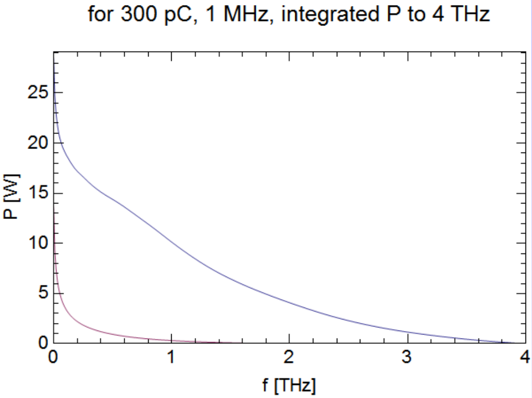


Figure : Integrated spectrum of power loss in the first cryomodule of L3. (The steady-state result is repeated in red.) About 50% of the power is above 100 GHz, 35% above 1 THz, 15% above 2 THz

Other Beam-Generated Radiation

- At the ends of L1, L2, L3, there are pipe transitions from radius $a = 1$ cm to $b = 3.5$ cm and back again. The loss factor for a matched pair of step transitions is $\varkappa = \frac{Z_0 c}{2\pi^{3/2}\sigma_z} \ln \frac{b}{a}$, giving 46 W radiated in L3.
  However, from numerical studies, one finds interference between these transitions and the transient wakes of the CM, and the net of this effect is reduced to < 10 W

- Two 3.9 GHz SRF CMs will be installed in LCLS-II. The layout of the CMs has not yet been decided. However, from work by I. Zagorodnov et al (TESLA Report 2004-01) we estimate that 13 W will be radiated by the beam per CM—it is small because the bunch here is relatively long and the CM is short

- In the last bend of BC2 (20 m upstream of the beginning of L3) the beam generates coherent synchrotron radiation (CSR). The steady-state CSR formula estimates that 50 W will be radiated toward the first CM. The formula that includes transients, however, yield a power loss of 110 W (see Gennady's talk)

Power Absorption Studies

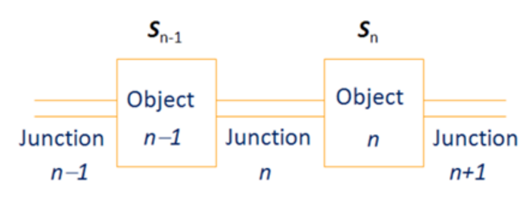
- Besides the superconducting cavities, there are intercavity bellows and connecting pipes (of SS) at 2K, and ceramic absorbers at 70K between cryomodules. One would like most of the power to go into the absorbers

- In L3, bunch spectrum reaches into THz. To cover this by brute force mode calculation is impossible. DESY developed a ray tracing program. Recently A. Saini, has been using an analytical diffusion model to estimate the power deposition (see Arun's talk)

- As with Euro X-FEL, in the LCLS-II cryomodules the SS surfaces (*e.g.* bellows and pipes) will be Cu plated

- In 2010 C. Adolphsen, C. Nantista, and I developed an S-matrix approach to estimate the fraction of power absorbed at 2K. We have repeated the calculation for the LCLS-II cryo configuration. We assume absorber has $\tan\delta = 0.18$ and $\epsilon_r = 15$ (don't know if this is realistic above 40 GHz). (HFSS calculations were performed by C. Nantista)

Smatrix Calculations of Power Deposition



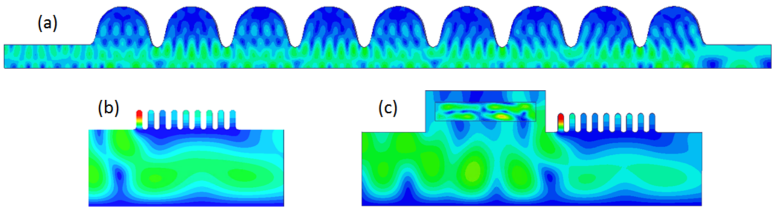


Figure : Cryomodule (CM) is constructed of objects connected by beam pipes. For a given frequency, first HFSS is used to find the S-matrices of constituent parts. Then the parts are cascaded together. The CM is driven by a signal moving at c through it. Bottom figure shows HFSS calculation for a cavity (a), a bellows (b), an absorber (c)

LCLS-II S-matrix Calculation Results

- Basic unit is 1 CM with its absorber. We use periodic BC's. Solved as matrix equation: $\mathbf{Ay} = \mathbf{d}$, with driving term $\mathbf{d}$ given by a wave in the first mode moving at c through the structure

Table : Percentage of HOM power deposited at 2K, p_{2K}/p_{tot}, at selected frequencies, according to S-matrix calculations and according to the analytical diffusion model of A. Saini. The last row (labeled "Total") gives the total analytical results assuming the steady-state spectrum of the L3 bunch.

f [GHz]	Copper (RRR=60)		Stainless Steel	
	S-matrix calc.	Analytical	S-matrix calc.	Analytical
4	0.75	0.35	19	13
8	3.5	0.55	49	18
12	0.5	0.70	23	21
16	0.55	0.85	10	24
20	1.1	1.0	47	26
40	1.1	1.6	35	33
Total		2.7		39

Mode Pattern at 4 GHz

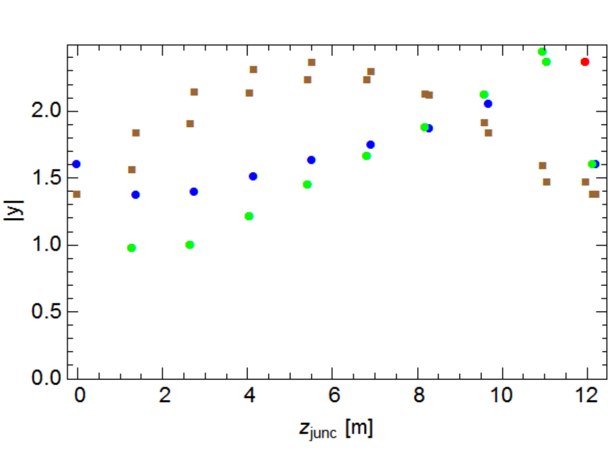


Figure : For $f = 4$ GHz, mode pattern where 0.75% of power is deposited at 2K. Wave moving to right is indicated for upstream junction of cavities (blue) and 2K lossy elements (green); brown gives junctions for wave moving to left. The red dot locates the absorber position.

Power Distribution at 4 GHz

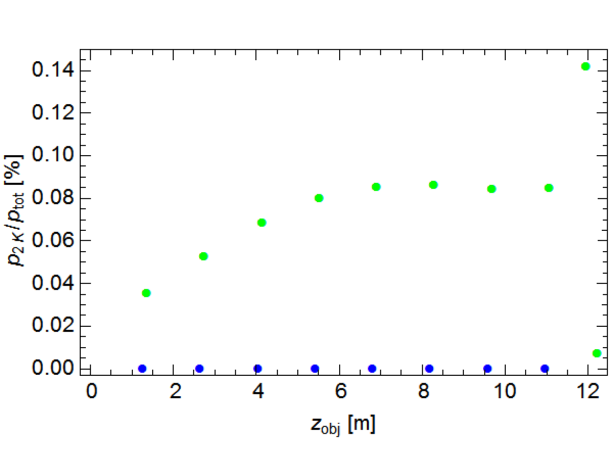


Figure : Power distribution for $f = 4$ GHz, where 99% of power is absorbed by ceramic absorber (offscale, at $z_{obj} = 12$ m). Cavities (their downstream positions) are shown in blue, 2K lossy elements in green.

Smatrix Results Cont'd

- As a poor man's way of estimating the average results over the frequency gaps, we've systematically added length to the cavity end pipes (up to a few cm's, in 2000 steps)

Table : After systematically varying the LCLS-II cavity end pipe lengths, the average, rms, and 9^{th} decile value of p_{2K}/p_{tot} according to S-matrix calculations with Cu plating (in [%]). Also repeated here for comparison are the analytical diffusion model results.

f [GHz]	Average	Rms	9^{th} Decile	Analytical
4	2.3	6.5	3.1	0.35
8	1.2	4.2	1.7	0.55
12	1.3	4.6	1.4	0.70
16	1.5	4.3	2.4	0.85
20	5.3	8.5	11.5	1.0
40	2.5	2.8	4.3	1.6
Total				2.7

Power at 2K vs Pipe Length

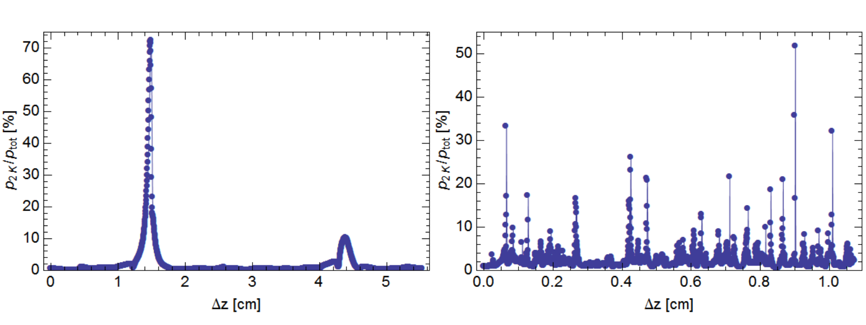


Figure : Percentage of power deposited at 2K, p_{2K}/p_{tot}, *vs.* added cavity pipe length Δz, at $f = 4$ GHz (left) and at $f = 20$ GHz (right)

An Example where Absorber is Inefficient

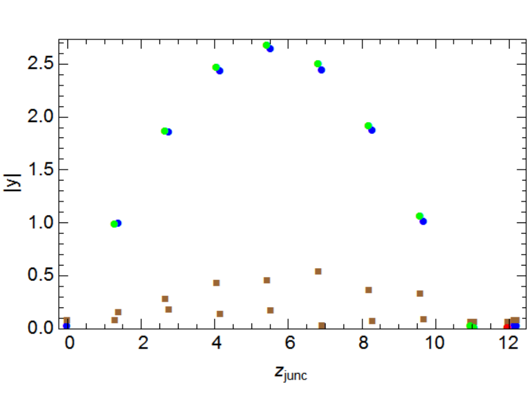


Figure : Mode pattern where 70% of power is deposited at 2K (for $f = 4$ GHz with 1.49 cm length added to cavity pipes). Wave moving to right is indicated for upstream junction of cavities (blue) and 2K lossy elements (green); brown gives junctions for wave moving to left. The red dot locates the absorber position.

Driving Term and S-matrix Plans

- Driving the system with a wave in only the first mode (moving at c through the structure) is not what the beam does. We tested the sensitivity of the results to this assumption: at $f = 16$ GHz we repeated the power *vs.* cavity pipe length calculation, but now driving one of the other three modes. The resulting average of p_{2K}/p_{tot} becomes 1.5%, 1.5%, 1.4%, 1.7%, when respectively driving mode 1, 2, 3, 4. The results do not seem sensitive to which modes are driven.

- G. Stupakov and I, with help from V. Dolgashev and S. Tantawi, are working on improved S-matrix calculations. Our goal is to:
  - use a field matching program to calculate S-matrices internally in *e.g.* a Mathematica program, which will allow us to do the power calculations over an extended frequency range
  - see if we can go up to 100 GHz (which covers 75% of the beam spectrum)
  - properly drive the modes as the beam would

Conclusions

- We have accounted for the HOM power loss in the superconducting linac of LCLS-II. At its maximum (with charge $Q = 300$ pC and repetition rate $f_{rep} = 1$ MHz) the steady-state power is 7.7, 10.7, 13.8 W/CM in the CMs of L1, L2, L3. The transient effect in the first two cryomodules of L3 yields 29.5, 14.5 W

- The beam spectrum in the steady-state has 50% of the power above 20 GHz, 25% above 100 GHz. In the transient case 50% of the power above 100 GHz, 35% above 1 THz

- We have briefly considered other sources of HOMs: the 1 cm to 3.5 cm pipe transitions, the 3.9 GHz SRF CMs, and CSR in the last bend of BC2

Conclusions Cont'd

- We have presented S-matrix calculations that address the question of absorber efficiency. We have done spot checks at 6 frequencies, that seem to be in general agreement with Arun's diffusion model and indicated that, if Cu plated, $\sim 98\%$ of the HOMs will end up in the absorber. However, we don't know if absorber properties above 40 GHz are realistic
- Improved S-matrix calculations are coming