BEAM DUMPS OF THE NEW LCLS-II *

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Abstract

In 2013 the design of the new LCLS-II new hard X-FEL facility at the SLAC National Accelerator Laboratory was rescoped to operate two parallel variable gap undulator lines at repetition rates up to 1 MHz. A new superconducting RF structure will be installed in the first third of the SLAC two-mile Linac to provide a few hundred kW of beam power at energies of up to 4 GeV. This paper describes the radiological aspects of the dumps that are being designed at the end of the electron beam lines. A layered arrangement of shielding materials is being optimized to reduce instantaneous dose leakage to occupied areas, minimum cool-down time to access the tunnel, and impact to equipment and to the environment. Calculations deal with numerous constraints, as legacy beam components will be used, and the existing tunnel structure was designed for beam powers fifty times below those envisaged for LCLS-II.

INTRODUCTION

The Linac Coherent Light Source (LCLS) delivers a hard X-ray Free Electron Laser (FEL) since 2009. LCLS-II will be a major addition to this facility, initially providing up to 240 kW of 4 GeV electrons at high repetition rates, distributed between an upgraded version of the LCLS-I line (e.g. variable gap undulators) and a new beam-line at the same tunnel. The LCLS-II main dumps will be installed at existing concrete pits in an underground building (Main Dump Hall, MDH), where LCLS-I is currently operating one beam-line at 500 W, which represents 10 % of the (LCLS-I) facility nominal power limit, and less than 500 times the nominal power of LCLS-II. This means that the LCLS-II dumps and their shielding need to be completely redesigned under severe spatial constraints.

DESIGN OF THE DUMPS

High power beams are stopped with large amounts of light media, like carbon and/or water, where the energy deposition is spread over larger volumes. In LCLS-II a heavier material must be used because space is limited. The preliminary design for the main dumps of LCLS-II consists of an aluminum slug with peripheral cooling, similar to that used in earlier facilities at SLAC. LCLS-II will exceed the power rating of previous designs, but this is partially compensated by using a higher purity alloy (Al-1100), which trades thermal conductance with the structural strength that was needed in machines with lower repetition rates. At 120 kW, and with snug shielding, the radius of the dump (R_d) needs to be large enough to prevent excessive heating of the dump shielding, but sufficiently small to effectively refrigerate the core. Radiation leakage with R_d=17.5 cm peaks at 2 W/cm^2, and it doubles if R_d is reduced by 5 cm. On the other hand, preliminary calculations with R_d=15 cm, water cooling on 40 % of the periphery at 60 dm^3/min and a 150 μm RMS beam, seem to indicate that the radius may need to be reduced (or some cooling brought closer to the axis) and the beam be spoiled to reach thermal equilibrium before the core melts.

RADIOISOTOPES IN GROUNDWATER

A fraction of the energetic neutrons generated at the dumps will penetrate through the building walls and will irradiate the surrounding ground. Spallation reactions on silicon and oxygen atoms will generate ^{3}H, ^{7}Be, ^{22}Na, etc. isotopes in soil and moisture. Some of those can leach into the percolating water and be slowly transported towards the water table, located 10 m below the dumps. Regulations demand that the concentration of such radioisotopes in water be not detectable even before dilution in the aquifer. To achieve that despite the dramatic increase of beam power expected for LCLS-II, normally the shielding around the radiation source would be accordingly augmented. However, LCLS-I local shielding inside the tunnel already occupies all transverse space, and expanding the building walls would be prohibitively expensive, as the building is underground.

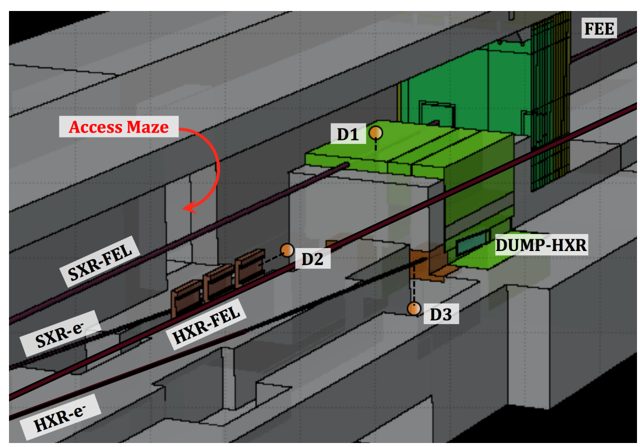

Figure 1: Flair [3] open 3D view of the LCLS-II Main Dump Hall.

With all of the constraints just described, the solution that was found to increase the lateral shielding of the dumps was to move them away from the walls and from the floor (by ≃ 30 cm). To do so, the vertical dipoles that deflect the beam to the lower dumps, must reduce their strength (by 1.1°) and be rolled inwards (by about 11°), as illustrated in Fig. 1.

With this modification, the potential radio-isotope production in soil is approximately attenuated by an additional factor $a = exp\left(\frac{7.87\,\mathrm{g/cm^3}}{161.5\,\mathrm{g/cm^2}} \cdot 30\,\mathrm{cm}\right) = 4.5$, which could be

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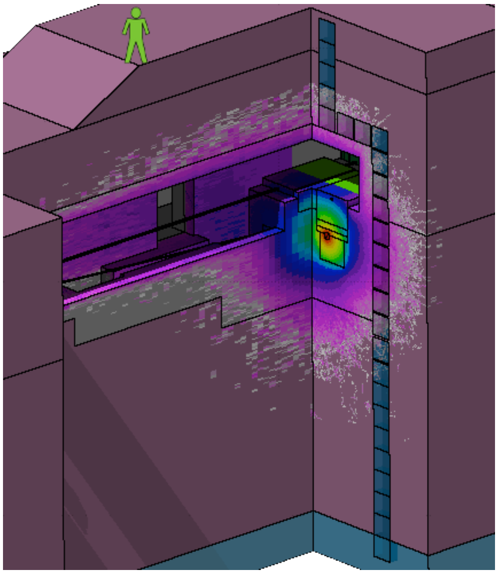

Figure 2: 3D rendering of the LCLS-II main electron dumps hall showing the prompt dose and the scoring volumes for isotope production and transport to the lower acquirer.

increased to $a = 15$ if instead of steel, tungsten filled that extra space. In any case, this would not be sufficient to offset the increase of power of LCLS-II. However, LCLS-I design was conservative, and did not account for the decay of isotopic concentration in humidity along the slow percolation towards the aquifer. A first-order model has now been developed to consider this effect.

Radioisotope production rates were computed with FLUKA [1, 2] for each of the (26) $1\,m^3$ boxes shown in Fig. 2, which represent the least shielded rain-water descent path to the aquifer. Neglecting contributions from parent radioactive chains (this is acceptable for ^3H and ^{22}Na), then the isotope concentration growth rate in water p_i is:

$$p_i = F_i \cdot E_f \cdot L_f \cdot n_e \cdot H/100 \tag{1}$$

Where F_i is the FLUKA simulated production rate [nuc./cm^3/e$^-$] in cell i of the dropping column of water ($i = 1$ is the top cell), E_f is an experimental correction factor to FLUKA predictions ($E_f(^3H) \simeq 2$, $E_f(^{22}Na) \simeq 1.5$) [4, 5], L_f is the isotope leaching ratio from soil to water ($L_f(^3H) \simeq 1$, $L_f(^{22}Na) \simeq 0.16$), n_e is beam electron rate on the dump (9.93×10^{13} e/s for 60 kW at 4 GeV), and H is the humidity percentage ($\simeq 20$ %).

Isotopes will be produced by the stray radiation, but they will also decay with $\lambda = ln(2)/T_{1/2}$. The following recurrent equation represents the evolution from one cell to the next:

$$N_{i+1} = N_i \cdot e^{-\lambda \cdot \Delta t} + \frac{p_{i+1}}{\lambda} \cdot \left(1 - e^{-\lambda \cdot \Delta t}\right) \tag{2}$$

Where Δ_t is the time step between two cells, which in turn depends on the percolation speed (v). Program *Evolve* was written to integrate equation (2) down to the aquifer level (N_{26}) as function v, and to print the corresponding activities, $A_{26}(v) = \lambda \cdot N_{26}(v)$. The results are shown in Fig. 3.

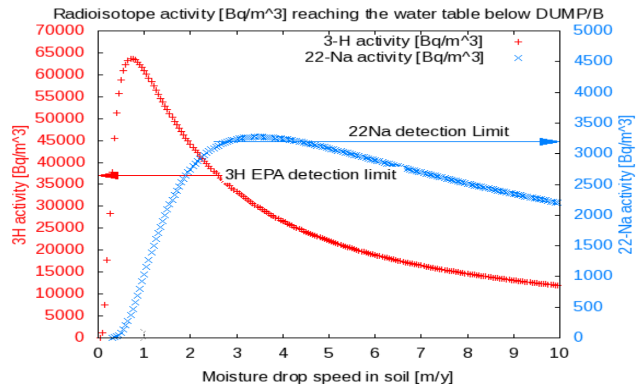

Figure 3: Activity [Bq/m^3] of ^3H and ^{22}Na in groundwater reaching the aquifer as a function of the percolation speed.

With this conservative build-up/decay model, peak activation values of 63 and 3.3 kBq/m^3 for ^3H and ^{22}Na were found for water migration speeds of 0.6 and 3.3 m/year. These values are well below the EPA drinking water limits (74 and 14.8 kBq/m^3, respectively), but they would exceed the corresponding detection limits (37 kBq/m^3 and 3.2 kBq/m^3). However, concentrations should decrease considerably if lateral diffusion towards less-irradiated areas would be considered along the vertical descent, but this effect is hard to quantify. Thus, in order to assure a low concentration, a hydro-membrane should be installed covering the top berm (and periodically inspected) so that direct rain-water flow near the dump area is minimal.

PROMPT DOSE

Dose Equivalent to Occupied Areas

Simulations were run with pulses equally distributed on each of the dumps, and fluences of neutrons, photons, muons were folded online with EWTMP dose equivalent estimators. The resulting dose rates (normalized to 2×120 kW) in the nearest areas that will be accessible during operation of the machine, i.e. on top of the soil berm (shown in Fig. 2), and at the down-beam experimental areas are well below the limits (0.5 μSv/h).

Dose to Electronics from Beam on Dumps

Simulations of the prompt dose leaking from the main dumps to the MDH suggest that annual neutron fluence will range from 10^9 to 10^{12} [n/cm^2/y] (depending on location), while 1-MeV neutron equivalent fluence in silicon will be an order of magnitude lower. Without local shielding, these fields, which show a 50-100 increase factor with respect to current LCLS-I values, may induce some damage to electronic devices with bipolar components, while semiconductors and CMOS may be spared. Table 1 displays the values for the three virtual detectors D1-D3 of Fig. 1.

As for electronic devices installed in the Front End Enclosure (FEE), which is separated by from the MDH by a thick iron + concrete wall, those will not be damaged by radiation.

Table 1: Annual prompt dose estimators (**n**eutrons (total), 1-MeV neutrons, high-energy **h**adrons and dose) from beam on dump. Detectors D1-D3 are shown in Fig. 1

Units	**n** [n/cm^2/y]	**1-MeV n** [n/cm^2/y]	**h>20 MeV** [h/cm^2/y]	**Dose** [Gy/y]
D1	2.4E12	2.1E12	2.0E11	3.6
D2	6.2E11	1.3E11	4.0E10	5.1
D3	2.2E12	4.4E12	9.4E10	14.0

RESIDUAL DOSE

Access to the MDH After Operation

An hour after beam shut-off, and prior to access, a residual dose rate area monitor in MDH will be read remotely to ensure activation levels are safe and As Low As Reasonably Achievable. Based on simulations, it is expected that by then most of the MDH will be below 50 μSv/h, except right in front of the dump. Table 2 shows the residual dose rates in detectors D1-D3 (as in Fig. 1) after **A)** 10 years of operation at average power and **B)** same as A, but followed by a day of irradiation at twice that power.

Table 2: Residual dose rates [μSv/h] in positions D1-D3 of MDH for the conditions described above

Access	**A**			**B**		
Cool-down	**1 h**	**8 h**	**24 h**	**1 h**	**8 h**	**24 h**
D1	8.1	4.4	2.8	12.2	5.5	3.0
D2	5.6	4.8	3.9	10.0	5.3	4.0
D3	51.1	35.6	21.9	67.0	42.6	23.9

Intervention Studies

High power dumps are more likely than others to be damaged by the beam. Moreover, due to the demanding heat transfer, coolant losses may be more frequent and more critical (higher activation spills, and potential burn-up of the target). But any kind of repair may either require long cool-down periods or high collective doses, unless interventions are carefully planed and the shielding is designed so that exposure is minimized during maintenance.

If a main dump has been irradiated for a year at top power (120 kW), and then needs to be extracted, residual dose rates 45 cm away from the front face would start at 1.6 Sv/h after 1 h cool-down and would remain above 36 mSv/h one year after. These high dose rates preclude normal handling and storage of the dump unit. A first mitigation would be to attach the immediate 10 cm of shielding around the dump to it, so that when the dump is extracted, it is already shielded. As seen in Table 3, this would somewhat reduce exposure at short and long cool-down times, but not so much in between because then decays from the activated shielding are significant. Instead, if the bare dump is inserted in an equally thick but 'fresh' shielding (located outside of the pit so it does not get activated) the radiation would be attenuated by $a \simeq 15$. Lead containers of the same thickness would further shield the dump ($a \simeq 100$). Combination of the two methods (pit+fresh shielding) could provide protection both during extraction and storage.

Table 3: Residual dose rate [mSv/h] at point M from a removed LCLS-II end dump after 1 year irradiation at 120 kW and 8 hour, 1 day, 1 week, 1 month and 1 year cool-down

Storage	**8 h**	**1 d**	**1 w**	**1 m**	**1 y**
Unshielded	350.8	193.1	50.2	40.3	36.7
Pit iron	119.2	76.1	51.9	36.8	7.4
Fresh iron	23.4	12.6	2.47	2.44	1.32
Fresh Pb	2.99	1.35	0.10	0.09	0.05

The shielding is being engineered so that it can be unstacked remotely with a crane, which should also move the dump to a container. Spare dumps should be built.

CONCLUSION

A set of key aspects for the design of high power dumps under space constraints has been presented. The design of LCLS-II dumps is ongoing and includes other aspects like air and cooling water activation, and ozone generation. Moreover up to twelve dumps rated from 3 W to 240 kW, and many collimators are currently being analyzed in similar terms.

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