RADIATION SAFETY ASPECTS OF THE LCLS-II ACCELERATOR AT SLAC

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ABSTRACT

The LCLS-II (Linac Coherent Light Source II) project at SLAC National Accelerator Laboratory will expand further X-ray Free Electron Laser science program in US and worldwide. For that, a new superconducting linac with MW power capability will need to be accommodated in the present accelerator complex. The usage of the existing infrastructure, where some sections are designed only for a low beam power and some have many service penetrations with direct line-of-sight to the beam, etc., make the implementation of the project challenging especially for the radiological impact of the LCLS-II beam operations as well as the choice of the radiation protection measures and controls needed to mitigate them. The paper introduces radiation safety systems and strategies employed at SLAC and describes in more detail different radiation shielding solutions to protect personnel and environment against prompt as well as residual radiation within LCLS-II project. For instance, shielding for locations with expected high beam losses, such as dumps and collimators, and shielding for various types of penetrations connecting accelerator enclosure with occupied areas. Moreover, the evaluation of radiation due to field emission from the accelerator cavities for radiological and machine protection purposes is also given. Finally, description of the Radiation Safety Systems at SLAC including the Beam Containment System and Access Control System and other systems required to protect personnel, public and the environment, is described as well.

KEYWORDS
LCLS-II, Radiation Protection, Shielding, FLUKA

1. INTRODUCTION

LCLS-II [1] is the new Linac Coherent Light Source II X-ray free-electron laser (X-FEL) facility to be constructed at the SLAC National Accelerator Laboratory. The existing SLAC linac and a new superconducting accelerator will provide electron beams that will generate bright a free electron laser of high coherence by passing electron beams through soft or hard X-ray variable gap undulator lines. The LCLS-II will expand and enhance the existing LCLS facility and thus it will offer wide range of applications in many scientific fields covering, for instance, nanoscale materials dynamics, study of chemical reaction and biological function in real time, investigation of material behavior in extreme conditions, etc. A compendium of new science opportunities enabled by LCLS-II X-ray lasers can be found in Ref. [2]. The new superconducting linac with MW power capability will be integrated in the present accelerator complex. The usage of the existing infrastructure, especially existing accelerator housing, where some sections are designed only for low power beam and some others have many service

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penetrations with line-of-sight between accessible areas and the beam line, make the implementation of the project challenging. The radiation safety systems applied to LCLS-II and specific shielding solutions to accommodate the rise of beam power are, for electron beam lines, described below. The radiation safety studies for LCLS-II experiment systems are given in [3].

2. RADIATION PROTECTION CHALLENGES

The LCLS-II facility consists of two accelerators that will be operated in parallel. The existing linac, which delivers up to 17 GeV electrons at 120 Hz with a maximum power of up to 5 kW, and a new superconducting linac providing electron pulses at rates reaching 0.93 MHz with energies up to 4 GeV. While the ultimate beam power capability of new linac may rise up to 1.2 MW, at the current phase of the LCLS-II project, the beam power will be limited to a maximal operation power of 250 kW, which will be distributed among the soft and hard X-ray lines. Thus only three high power dumps, one designed for 250 kW and two dumps with a maximum power of 120 kW each will be installed to terminate the electron lines. Since no MW dump will be used, the accelerator system will rely heavily on safety interlocks with fast response and shut-off times for beam mis-steering events. Due to the high average beam power many beam line components, such as collimators and dumps, cables, cooling water systems, etc. will be highly activated and therefore an efficient shielding against residual radiation needs to be designed and added to many locations. At the same time, areas with higher beam losses have to be identified and adequate shielding must be used to reduce prompt radiation outside of the tunnel enclosure down to acceptable levels and thus to mitigate dose to personnel, to the public as well as the environmental impact (soil, groundwater, and air activation). Finally, every effort is made to use the existing infrastructure to accommodate the new beam lines, especially linac accelerator housing which is cluttered with existing accelerators systems, has insufficiently thick walls in some locations and a large amount of penetrations.

3. RADIATION SAFETY SYSTEMS AT SLAC

Radiation Safety System (RSS) [4] at SLAC shall ensure that workers, users, general public and the environment both on-site as well as off-site of the laboratory are protected from radiation from accelerator and beam operation. Moreover applicable regulations should be met and radiation doses must also be maintained As Low As Reasonably Achievable (ALARA principle). RSS is a combination of active and passive safety systems used to protect personnel from prompt radiation. It consists of Active Control Systems (ACS), which prevent access to secured areas when beam is possible or present, and Radiation Control Systems (RCS) requiring beams to be contained in prescribed channels and limiting the beam power and losses to prevent excessive radiation within occupied areas. ACS consists of access control, beam shut off ionizing chambers, beam stoppers, emergency buttons, while RCS is composed of shielding, protection collimators, magnets, devices limiting the total beam power (e.g. toroids) and beam losses (current comparator, ionizing chambers). All safety systems are designed for operation of the existing linac and new superconducting accelerator in separate as well as in combine mode.

4. RADIATION FROM ACCELERATOR CAVITIES

The strong electromagnetic fields in the superconducting radio-frequency cavities lead to substantial field emission. FLUKA [5, 6] Monte Carlo code was customized to perform the radiation transport between cryomodules (each cryomodule has eight cavities) and Track3P [7], the standalone tracking code developed at SLAC was used to compute the electron transport within the RF regions. Detail description of the calculation technique including impact to the machine components and radiological aspects can be found in Ref. [7]. Here, only radiation protection conclusions are summarized.

The prompt and residual radiations around superconducting linac are show in Fig. 1. During cavity operation dose-rate levels inside tunnel are very high, up to 1 Sv/h on contact (see Fig. 1 top), and therefore personnel can access an accelerator area only if all cryomodules are off and fully de-energized. This applies even during commissioning of individual cavities. Figure 1 bottom shows the residual dose rate after a long run with 10 nA/cryomodule captured current for several cooling times. It was found that residual dose rates are significantly higher than those initially estimated without captured current acceleration. After 1hour beam-off, which is the default cool-down at SLAC, the residual dose rates are in the order of 10 μSv/h and therefore special access requirements to the area are not expected.

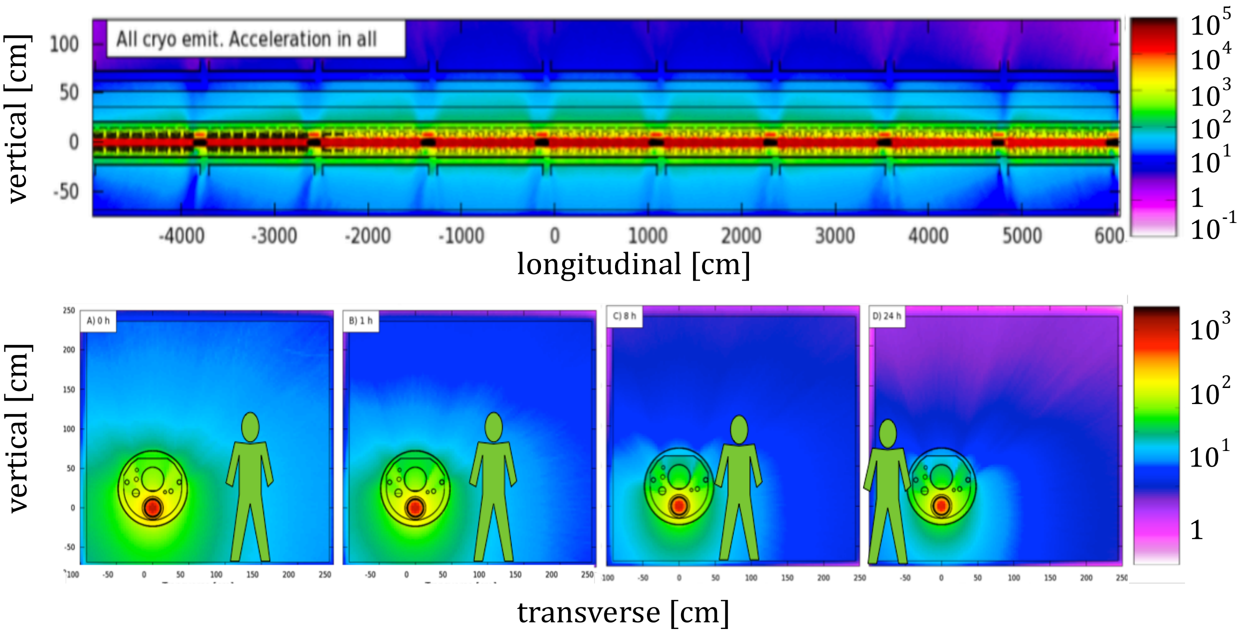

Figure 1. Prompt [mSv/h/10nA] (top) and residual [μSv/h/10nA] (bottom) radiation fields around superconducting accelerator cavities.

5. RADIATION STREAMING THROUGH PENETRATIONS

The accelerator enclosure is connected with the ground level Klystron Gallery by several hundreds of straight penetrations, which were constructed for supporting services of the previous SLAC linac. Most of these penetrations will be also used for the new superconducting accelerator, for routing of cables, wave-guides ducts or for ventilation in eventual helium spills. The location of the legacy penetrations with respect to the accelerator is such that, in many cases, requires installation of additional shielding. The amount and layout of the shielding depends on the distance between penetration and the beam-line, maximum credible incident (MCI) loss in a given section and the number and arrangement of conduits passing through the penetrations. For instance, assuming MCI of 2 MW and a line-of-sight between a beam loss point and the gallery, the penetration must be shielded by 90 cm of concrete or 30 cm of iron, respectively. An engineering implementation of such shielding is shown in Figure 2 right. On the other hand, some penetrations that are relatively far from the beam line do not require any shielding. Figure 2 left shows dose rate maps for penetrations with and without line-of-sight, where dose rates above the penetrations differ by 5 orders of magnitudes [8].

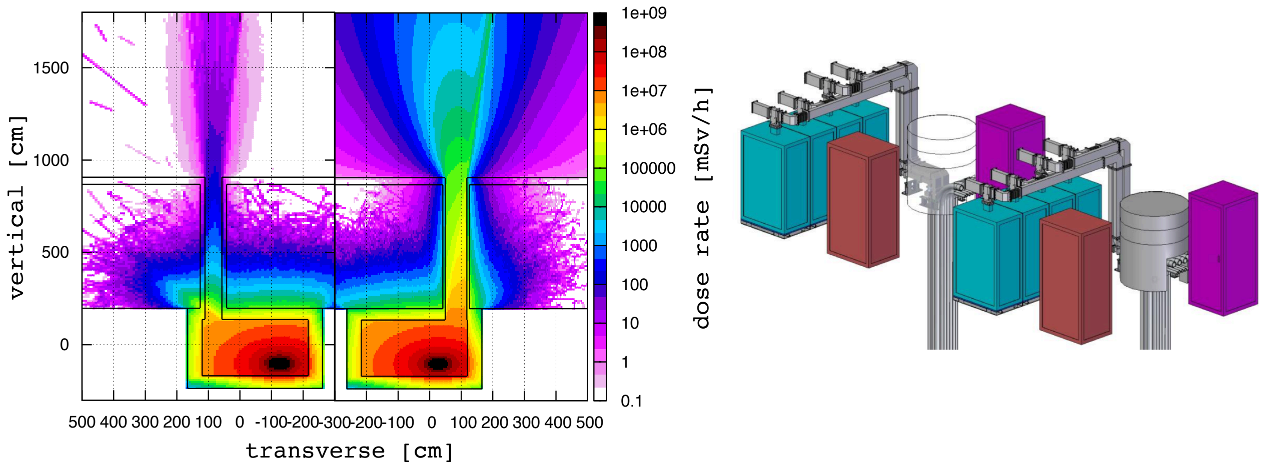

Figure 2. Left: Dose rate maps for South and North penetrations calculated for 2 MW 4 GeV beam. Effect of a line-of-sight is clearly seen in case of North penetration. Right: Engineering implementation of the shielding cap placed on the top of the penetration.

6. HIGH POWER DUMPS

Three high power electron dumps with beam powers of hundreds of kilowatts (one 250 kW, and two 120 kW each) and their associated shielding are a major aspect of the LCLS-II facility. Their shielding was designed to ensure that radiation levels in neighboring accessible areas preserve existing radiological classification, that residual doses one hour after beam off comply with laboratory policy and so that there is no impact on the environment. The later includes also evaluation of radioactive air exhausted into the atmosphere and production of radioisotopes in soil, which could eventually reach the groundwater, located about 10 m below the main dump pits. The design aim was not only to fulfill legal limits for drinking water (e.g. 740 Bq/dm^3 for H-3) but also to remain below a detectable threshold (37 Bq/dm^3 for H-3) in accordance with the ALARA principle. Therefore radioisotope production rates, coupled with a conservative, build-up/decay hydrogeological model for a hypothetical groundwater column trajectory, dropping from the surface towards the water table at constant speed were also included in the analysis [9].

Figure 3 top describes the shielding solution for the 120 kW dumps that preserves the integrity of the main dump hall concrete structure and complies with above mentioned radiological aspects. To accommodate necessary shielding, the dump lines will be raised and bent inwards to increase the available space for shielding between the dump and the nearest soil. To compensate for the increased beam power and for the elevated location of the dumps, 30 cm of concrete and 120 cm of iron need to be added on the top of the dumps in order to provide an effective shielding against residual radiation (see Fig. 3 bottom) as well as for prompt radiation. Moreover, the top part of the shielding serves also as a collimator for passing photons lines. Finally, the shielding is being designed to allow unplugging the cooling circuits and other services and swiftly replacing dump core easily in case of its failure. This operation can be done remotely minimizing personnel and collective intervention doses.

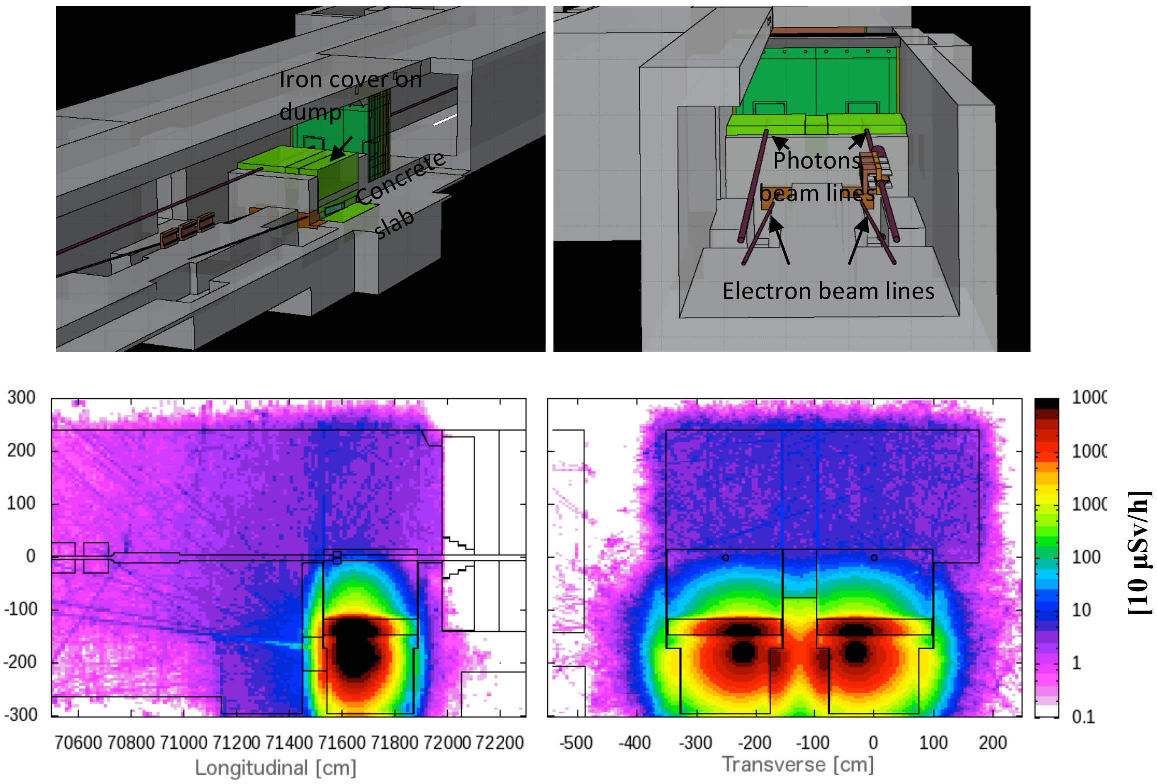

Figure 3. Top: FLUKA model used for LCLS-II main dump hall simulations. Shielding consists of concrete (gray) and iron (green) layers. Bottom: Elevation and cross section residual dose rate maps [10 µSv/h] for 1 day of operation at 2 x 120 kW, and 1 hour cool-down.

7. COLLIMATION SYSTEM

In a high power X-FEL machine, continuous radiation fields like that from gas-bremsstrahlung interactions, field emission, intrabeam scattering, etc. may lead to demagnetization of undulator permanent magnets. In order to reduce dose to undulators, a multi-stage collimation system consisting of more than 30 adjustable halo collimators will be employed [10]. Showers initiated by those beam losses at the halo collimators (typically ranging from several to tens of watts) may irradiate the soil that surrounds the Linac tunnel, eventually making activity of radioisotopes become detectable. Moreover, the collimators and the tunnel wall may get activated, leading to excessive residual dose rates during access of personnel at typical cool-down times. Therefore, it was necessary to examine whether these effects take place, and if so, how much local shielding is necessary around each halo collimator to mitigate the potential risks. Since there is a large number of collimators and each of those presents unique irradiation conditions, a sophisticated program that compute the specific collimator shielding was developed. It is based on parameterized formula delivered from FLUKA Monte Carlo studies for various input parameters such as energy (between 100 MeV and 4 GeV), power loss, collimator material (Ti, Al, Cu, W), several shielding materials (e.g. concrete, Fe, Pb, etc.), and distance from tunnel walls. This approach allows updating the shielding requirements reflecting the latest estimation of beam power losses or change of collimator location or its jaws material. For instance, it was found that for losses in the range of tens of watts, the shielding thickness is dictated by residual dose, while for losses of several hundreds of watts it is dictated by ground water protection. A detailed explanation of the calculation technique and complete results will be provided in a separate publication.

8. CONCLUSIONS

The LCLS-II will add capabilities and capacity to the already successful LCLS science program. The radiological analysis for LCLS-II has been conducted for personnel and environmental protection taking into account the ALARA approach, and leveraging experience from existing LCLS design and operations as well as past high power beam operations. Shielding requirements have been developed for most systems by means of state of the art Monte Carlo codes such as FLUKA, and analytical methods. Radiation from field emission of superconducting cavities including captured current acceleration has been studied from both radiological and machine protection perspective. Constraints posed by designing a new machine in the existing tunnel have been considered in the design and examples of shielding solutions for linac penetrations, high power dumps and collimators were described. The radiation protection studies for the experiment systems are given in [3]. The LCLS-II project design is mature and it is going to move into engineering and implementation phase.

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