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Radiation Safety Aspects of LCLS-II Accelerator at SLAC: Containment of Electron Beam

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Abstract

LCLS-II project [1] currently underway at SLAC will provide new capability as well as new capacity to the existing Linac Coherent Light Source (LCLS) Free Electron Laser. The project will add a new 4 GeV continuous-wave superconducting (SC) linear accelerator capable of generating up to 1 MHz, 1 MW of average beam power to SLAC accelerators. However, only 120 kW of beam power will be delivered to each of the two electron beam dumps after passing through each of two new variable gap undulators. The existing LCLS Linac, which is a copper based Linac located in the last kilometer of the SLAC Linac tunnel, will retain its capabilities and continue to operate at 120 Hz, up to 5 kW and up to 17 GeV.

LCLS-II will be installed in the existing SLAC linear accelerator housing, parts of which were shielded for lower LCLS average power beams. SLAC Radiation Safety System (RSS) [2] that is comprised of shielding, Access Control System and Beam Containment System (BCS) assures safe transport and operation of high power beams through the entire facility such that the design goals for radiation safety are met.

All accelerator facilities use shielding, Access Control System and interlocked radiation monitoring outside shielding as part of their standard radiation safety systems. At SLAC, BCS is a main component of RSS and is implemented as a complement to shielding. The role of BCS in LCLS-II radiation safety for the electron beams is described.

Introduction

The subsystems for the LCLS-II SC accelerator including RF gun, superconducting Linac segments L0-L3, and bunch compressor chicanes BC1 and BC2 will be installed in the first 700 meters of the existing 3 kilometer long SLAC Linac underground housing.

The SC Linac beam will be transported through the other 2.3 kilometers of existing accelerator tunnel to the Beam Switch Yard (BSY). Pulsed magnets can direct pulses of electrons to a new BSY dump which can absorb up to 250 kW of beam power at 4 GeV. Electron beam pulses will be transported further through the over-the-ground structure, Beam Transport Hall (BTH), to two new adjustable gap polarized undulators. After passing through the undulators, beams will be bent down into two high power beam dumps capable of absorbing 120 kW each. Fully coherent X-rays covering the spectral ranges 0.2-1.2 keV for Soft X-Ray (SXR) lines and 1-5 keV for Hard X-Ray (HXR) lines will be transported further to instruments in experimental hutches.

Figure 1 shows a schematic of the SLAC linear accelerator facility including the layout of the new LCLS-II accelerator. The SC Linac beams can simultaneously be transported to the two undulator lines and the BSY dump. Additionally, LCLS-II can operate simultaneously with the current LCLS Linac.

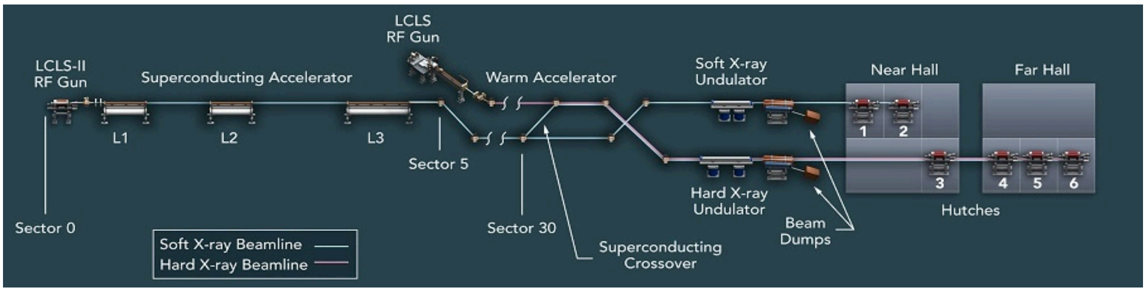

Fig.1 - Schematic of SLAC linear accelerator facility including the layout of the new LCLS-II accelerator

Installation of the LCLS-II accelerator and beam lines in a pre-existing facility constrains implementation of some of the controls for the radiological hazards [3]. Some of these constraints are:

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- There is nearly a direct line of sight from many of the 450 penetrations in the Klystron Gallery, an occupiable area by workers to the SC accelerator beam line,
- The 300-meter-long above-the-ground BTH as well as Dump Hall and Dump Pit had been designed for LCLS operations (5 kW of average beam), but now will need to house safe operation of 2 LCLS-II beams, 120 kW each,
- Average beam power in accelerator can reach up to 1 MW, and BCS interlocks must be relied upon to transport and distribute power in several lines that can only accept up to 120 kW each,
- Fast shut-off time (~ ms) is required to terminate errant beam conditions as the beam repetition rate increases from 120 Hz to 1 MHz.

Different approaches in controlling prompt radiation hazards and deployment of BCS to manage safe transport of LCLS-II beams through the BTH will be discussed in more details in the next sections.

Radiation Safety Systems in Accelerators

Beam losses in accelerators are the main source of radiation hazard; they are categorized as normal (expected) or abnormal beam losses. Normal beam losses consider interaction of beam and beam halo with devices such as collimators, wire scanners, screens and dumps, losses on bending magnets and septa in the dump lines. Abnormal beam losses can occur when a larger fraction of beam than is expected (up to full beam power) is lost at various locations along the accelerator, or in transport lines.

Examples of conditions that could lead to abnormal beam losses include failure or a wrong setting of power supply, wrong setting of polarity of magnets, mis-alignment of beam line components, mis-match of energy of incoming beam and beam line setting.

In many instances, abnormal beam losses do not result in high integrated doses outside shieling enclosures as Machine Protection System (MPS) interlocks are expected to terminate such cases. But reliance on MPS for personnel protection can put personnel at higher risk than is accepted in many facilities. Additionally, most regulatory agencies, as well as best management industrial practices [4] require design, review and performance requirements for critical safety systems (e.g. configuration control, redundancy, fail safe, documentation, review, approval) which are not required for MPS in most accelerators.

High normal beam loss locations (beam dumps, target areas, collimation sections) are sufficiently shielded in accelerators, but many facilities, including most synchrotron light sources, are not shielded for abnormal loss of full beam power (or a large fraction of the beam) along the entire facility. This is mainly due to practical considerations such as lack of space, cost, etc. and is the case for LCLS-II at SLAC in which addition of bulk shielding outside, or local shielding inside the pre-existing facility is not feasible. In such cases, other measures need to be taken to ensure abnormal beam losses do not result in excessive radiation levels outside shielding enclosure. A challenging issue for accelerator and beam line designers is the control of abnormal beam losses. An issue that often arises is the following: should the radiation levels from abnormal beam losses be controlled (attenuated) by use of sufficient shielding (passive systems) for abnormal beam losses, or should active systems be deployed to detect and terminate the hazard?

The answer to this question is the deployment of a combination of passive system (mainly shielding) and active electronic interlocks [2,4].

The degree to which a facility can rely on active systems to supplement shielding varies in different facilities (active vs passive systems). It should be stated unequivocally that shielding (passive system) is the preferred choice. In general, the reliability or integrity of shielding is assumed to be very high, but the reliability of active protection systems needs to be demonstrated for each particular design.

SLAC Beam Containment System

Radiation safety for sections of LCLS-II beam line relies on implementation of the BCS to control prompts radiation hazard. SLAC BCS is a combination of mechanical devices and associated electronic protection devices that ensure beam is confined within an approved beam channel at an approved allowed beam power, thus preventing excessive level of radiation in occupied areas [2]. BCS also provides protection for critical safety devices such as personnel safety stoppers (shutters) and is distinct and separate from the MPS.

A key function of SLAC BCS is preventing errant (mis-steered) beams from striking the shielding enclosure. Examples that illustrate the importance of containment of mis-steered beams were presented in the 7th International Workshop on Radiation Safety at Synchrotron Radiation Sources. They included an event during Linac commissioning of one facility at 1.5 watts, 100 MeV in which electron beam mis-steering due to the mis-match of beam energy and dipole setting resulted in 17 mSv/h outside a shielding wall [5]. Another event was reported in a different facility, in which a 2.1 watts, 250 MeV beam mis-steered by dipole with wrong polarity resulted in 22 mSv/h outside a shielding wall [6].

A potentially serious situation also occurred at SLAC several decades ago in which a magnet with reverse polarity allowed the primary electron beam of ~20 GeV, 30 W to escape its proper transport enclosure and hit the concrete wall instead of the beam clump. High-intensity radiation (3.6 Gy/hr) was measured outside of a 1.8 meter thick concrete enclosure [7].

It should be stressed that none of these events resulted in any significant doses to personnel.

The consequences of a hypothetical LCLS-II mis-steered scenario for beam striking the BTH wall (see Figure 2) were evaluated using FLUKA (4 GeV and 120 kW electron beam striking the 1.8 m thick concrete wall at 80 mradian). Results show that the dose rate from such a scenario will reach as high as 1000 Gy/h behind the wall (assumes several BCS failures combined with beam mis-setting).

While such a scenario may be deemed to be impossible or not-credible, the above examples illustrate the point that any mis-steered beam that could lead to unexpected high radiation levels outside the shield must be contained.

LCLS-II Beam Containment System

An example of use of BCS is given to illustrate the approach to radiation safety in LCLS-II. The BTH which is a 300-meter-long structure above ground represents a special challenge. It was designed for LCLS beam parameters (less than 5 kW of average beam power) and is not sufficiently shielded for the much more powerful LCLS-II beams (2x120 kW at 4 GeV, with the potential upgrade to 2x240 kW at 8 GeV). Of special importance is preventing the errant (mis-steered) beams from hitting the walls.

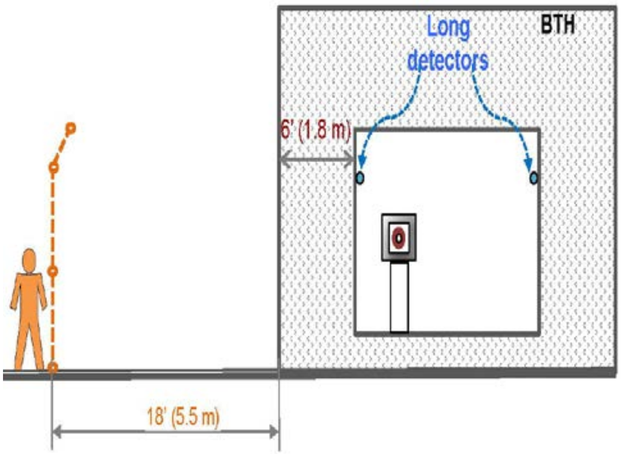

Fig.2 – (L) Schematic of LCLS Beam Transport Hall (BTH) designed for 5 kW. Fence will be added for LCLS-II operations; (R) photo of BTH- 2x120 kW beams will be transported from left to right

Extensive ray-trace studies for LCLS-II were performed using FLUKA [8,9] Monte Carlo code and the MadFLUKA [10] Beam Line 3D Builder. MadFLUKA generates FLUKA-compatible geometries from MAD files and automatically inputs the optics lattice. The envelope of mis-steered rays in BTH section of LCLS-II was computed and the location and size of BCS protection collimators were determined that would intercept the envelope of the errant rays.

List of conditions that could results in errant beams was used to generate the ray-trace of LCLS-II include: energy, magnetic field mis-match; wrong polarity, quadrupole short circuit and misalignment, sextuple and corrector failure [11, 12].

Results of ray-trace studies for the LCLS-II beam in SXR are shown in Fig. 3. The figure in the left shows results of the ray-trace studies considering the above errors. The right figure shows how properly located protection collimators (total 15) will intercept and contain the mis-steered rays.

Protection Collimators (PC) used in conjunction with BCS are typically between 5 to 20 cm thick of steel. A main function of the PCs is to “spoil” the beam such that an errant beam is prevented from striking and burning through shielding barriers and generating high dose rates outside shielding enclosures.

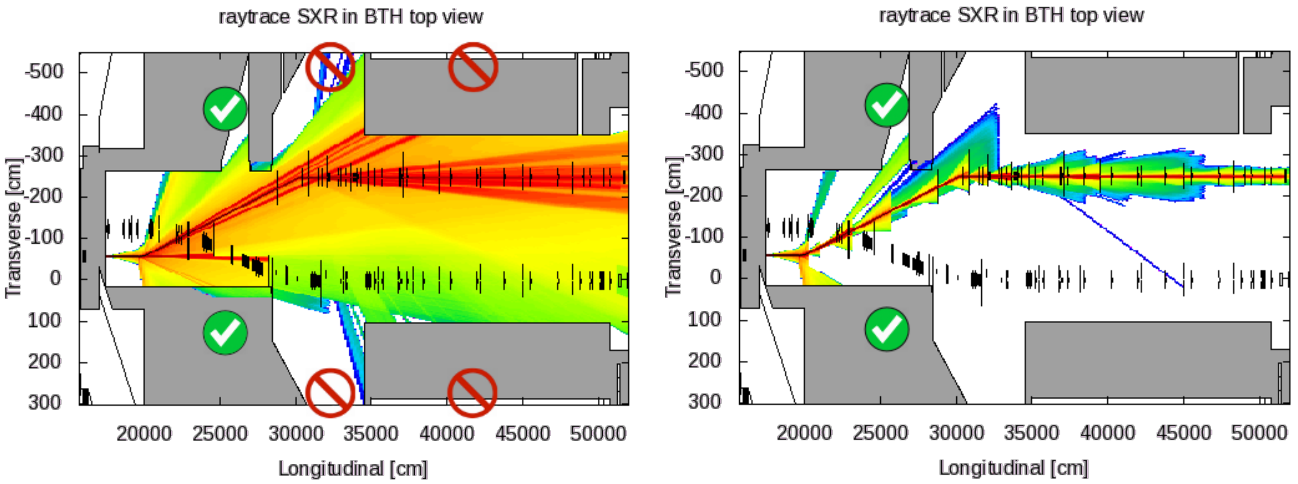

Fig.3 – (L) ray-trace studies for the LCLS-II beam in SXR (without protection collimators); (R) ray-trace studies for the LCLS-II beam in SXR (with protection collimators)

In the BTH studies given above, if the mis-steered ray is intercepted by a Protection Collimator, the dose rate for the same accident scenario will be reduced from 1000 to 2 Gy/h. Radiation detectors such as ion chambers or other appropriate sensors are placed close to the PCs to trip the beam in a very short time (~ms) limiting the integrated dose in such a case to about 1 μSv.

The lateral size of the PC (see Fig. 4) is determined by the energy limit of the incoming beam. The lower (and the upper) limit of the energy of errant beams, corresponding to the ray-trace study conditions, is bounded by using another type of BCS sensor, Magnet Current Monitors (MCMs), that monitor current in dipole magnets and trip the beam if the current is outside of its allowed range.

PCs are also equipped with a Burn Through Monitor (BTM) over as large an area as the beam can be steered. BTMs are pressure vessels, usually located near shower maximum, or at the down-beam end of the collimator. The BTMs are designed to rupture when the device being protected absorbs greater than its allowed beam power, and provide an additional layer of protection. The pressure vessel is the “active” element and consists of an austenitic stainless steel container, which is thin-walled and thin in direction of beam propagation.

The BTM pressure vessel is also connected to a remotely located electro-mechanical pressure switch which will trip the beam when the beam has perforated the vessel. The BCS requirements for LCLS-II have been specified [13,14]; the system (sensor, logic, mechanical devices and shut-off paths) are being designed and will be implemented to meet these requirements.

Fig.4 –Protection Collimator, Burn Through Monitor and Ion Chamber deployed in LCLS

Summary

LCLS-II is a high-power machine that will be installed in an existing facility, parts of which are shielded for lower power beams. Design and implementation of radiation safety systems for LCLS-II requires use of advanced tools, new technologies as well as detailed studies to augment shielding. An example of the application of BCS is the use of protection collimators to contain the mis-steered beams. These collimators will attenuate and spoil the electromagnetic shower away from the shielding enclosure, trigger shut-off of the beam by point detectors placed next to it, and shut-off the beam in case of burn-through. SLAC BCS will play a key role in assuring radiation safety for LCLS-II beam operation.

Acknowledgement

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