RADIATION PROTECTION ASPECTS OF THE LINAC COHERENT LIGHT SOURCE FRONT END ENCLOSURE*

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Abstract

The Front End Enclosure (FEE) of the Linac Coherent Light Source (LCLS) is a shielding housing located between the electron dump area and the first experimental hutch. The upstream part of the FEE hosts the commissioning diagnostics for the FEL beam. In the downstream part of the FEE, two sets of grazing incidence mirror and several collimators are used to direct the beam to one of the experimental stations and reduce the bremsstrahlung background and the hard component of the spontaneous radiation spectrum. This paper addresses the beam loss assumptions and radiation sources entering the FEE used for the design of the FEE shielding using the Monte-Carlo code FLUKA. The beam containment system prevents abnormal levels of radiations inside the FEE and ensures that the beam remains in its intended path is also described.

INTRODUCTION

Description of the Facility

The Linac Coherent Light Source at SLAC National Accelerator Laboratory is the world first hard X-ray Free Electron Laser (FEL). In order to obtain the extremely short and low-emittance electron pulses necessary to generate the FEL beam, a photoinjector and a pre-accelerator linac were built in the off-axis injector vault at sector 20 of the 2 mile long LINAC. In addition, two chicane bunch compressors were added in the last kilometer of the accelerator. With those modifications, the accelerator is able to deliver electron bunches with an energy ranging from 4.3 GeV to 14.3 GeV with a 3.4 kA peak current. The electron beam is then taken through a Beam Transport Hall (BTH) to the 130 m underground Undulator Hall (UH), which hosts 33 undulators. The electron beam oscillations through the undulator generate FEL and spontaneous photons. After the UH, the electron beam is electromagnetically bended toward a shielded beam dump while the straight ahead beam line brings the spontaneous and FEL photons to the Front End Enclosure (FEE). In addition, high energy bremsstrahlung generated by electron beam losses in collimators, diagnostic devices or other targets inserted into the beam path enters the FEE. The upstream part of the FEE hosts a set of adjustable slits and an attenuator system as well as the diagnostics for the FEL beam. In the downstream part, a set of six mirrors is used to deliver the beam to one of the three beam line branches going to the six experimental stations. The experimental stations are located in the six hutches of the Near Experimental Hall (NEH) or Far Experimental Hall (FEH). The layout of the FEE showing the items fulfilling a radiation safety function is shown in Figure 1.

Overview of the Radiation Protection Aspects of the LCLS

Among other functions, the responsibility of the Radiation Protection Department (RPD) at SLAC is to ensure that any dose above background to workers or to the environment resulting from the operation of accelerators is As Low As Reasonably Achievable (ALARA) and below the regulatory limits. When planning the construction of a new facility like LCLS, this responsibility implies working with the accelerator physicists to estimate beam losses and design appropriate shielding to mitigate prompt and residual radiations. In addition, the RPD specifies the requirements of the Personnel Protection System (PPS) which prevents personnel access into high radiation areas inside the accelerator housing. This system is not described in the present article. The RPD is also involved in the design and review of the Beam Containment System (BCS), which prevents abnormal beam losses and high radiation levels inside occupied areas by confining the beam to an approved channel at an allowed beam power. Most of the radiation protection issues related to the LCLS construction are commonly encountered at SLAC and are not specific to FEL machine. For the LCLS design, different softwares as the analytical SHIELD11 code [1] or the Monte-Carlo codes MARS [2] and FLUKA [3] were used to determine the shielding requirements for the accelerator housing and the different beam dumps. In particular, over 600 m of the LCLS tunnel were implemented as a FLUKA geometry using a realistic description of the building walls, access mazes and most of the beam line components as electromagnets, collimators, undulators, and the three beam dumps. In parallel, the FLUKA code was also used to perform calculations of the dose to electronic components inside the accelerator housing and to the permanent magnets of the undulators in order to estimate the potential undulator performance loss due to radiation damages [4].

The radiation safety aspects of the FEE and experimental hutches operation are more specific to FEL facilities. Indeed, the presence of personnel occupying the experimental floor near 0 ° with respect to the electron beam line

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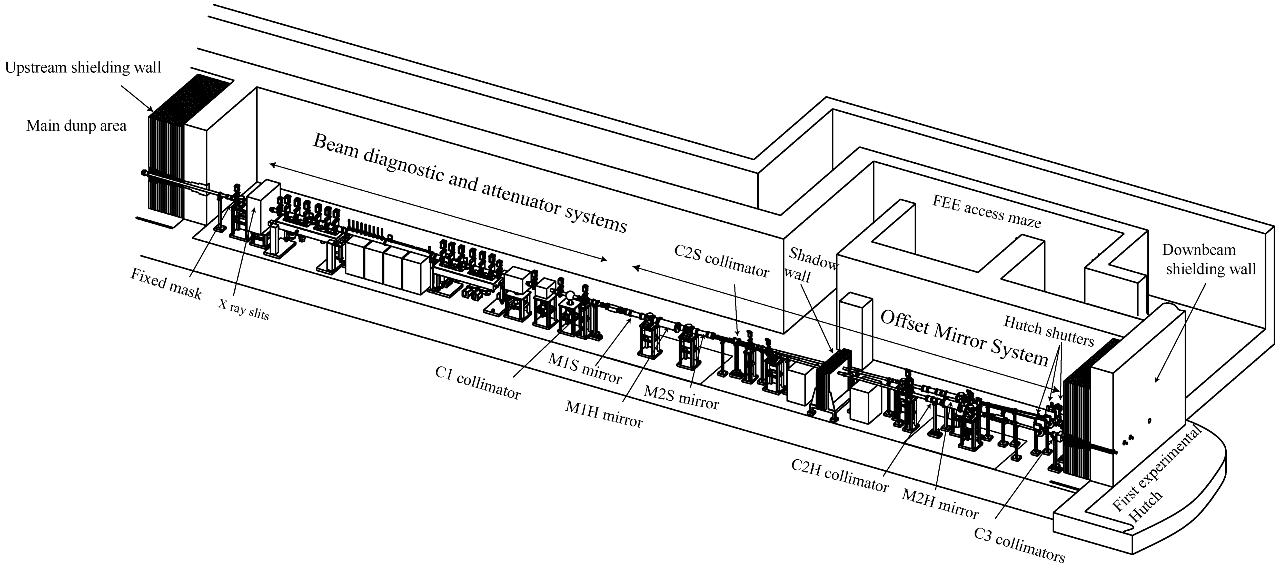

Figure 1: Layout of the FEE with the FEL diagnosctic equipment and the Offset Mirror System.

is not usual in accelerator facilities. The BCS system and shielding elements described in the following sections must ensure that the dose rate inside the first hutch due to radiations entering the FEE remains below the annual dose limit of 1 mSv enforced at SLAC for that type of area.

RADIATION SAFETY ASPECTS OF THE FEE

Radiation Sources Entering the FEE

As it was already mentioned, the electron beam is steered-down to the main electron dump after the UH by using powered bending dipoles. In case of bending magnet failure, the resulting errant beam is diverted by the electron safety dump line berfore it can reach the FEE downstream. The electron safety dump line consists of three permanent magnets, several collimators protected with Burn Through Monitors (BTMs) and Protection Ion Chambers (PICs) and a beam dump. The BTMs are in place to shut-off the beam if one BCS device (collimators or the safety dump) has melted. The PICs fulfill the same function if an abnormal beam loss is detected. It should be noted that the dumpline vertical bend magnets are also connected in series with the dog leg bend magnets in the BTH to impede electron beam delivery to the safety dump line, thereby reducing challenges to the BCS system. Since the safety dump line ensures that no electron enters the FEE, only spontaneous photons as well as FEL photons from the electron beam going through the undulator and bremsstrahlung photons line will enter the area.

The characteristics of the spontaneous and FEL beam for the nominal operating parameters corresponding to either the minimum FEL energy for soft X-ray experiments (4.3 GeV electron beam and 830 eV FEL beam) or maximum FEL energy for hard X-ray experiments (13.6 GeV electron beam and 8.3 keV FEL beam) are detailed in Ref. [5]. Using an emittance equal to 1.2 μm and a peak current of 3.4 kA for both cases and the LCLS undulator parameters, it is found that the maximum FEL energy per pulse is equal to 2.2 mJ for electron beam operation at 13.6 GeV (FEL first FEL harmonic at 8.3 keV) and to 5.0 mJ at 4.3 GeV (first FEL harmonic 830 eV). The spontaneous photon energy per pulse was found equal to 22 mJ using a 1 nC charge per electron bunch, for the nominal maximum energy of 13.6 GeV. Using the maximum repetition rate of the accelerator (120 Hz), the average FEL and spontaneous powers can be derived.

The amount of bremsstrahlung power entering the FEE depends on electron losses upstream of the FEE and on the use of beam diagnostic devices in the electron line. Beam losses in the collimators and in the vacuum chamber of the first bending magnet deflecting the electron beam to the main dump were estimated to be equal to 20 W. The three wire scanners before the UH and the beam finder wires (40 μm diameter carbon wire) installed in front of each of the 33 undulators were also taken into account. FLUKA was used to calculate the maximum amount of bremsstrahlung power into the FEE for those different losses. Results are summarized in Table 1 considering the maximum authorized beam power. It should be noted that, in practice, those values are not reached as the repetition rate of the accelerator is limited when beam diagnostic devices are being used in order to reduce the dose to undulator magnets as well as to limit the dose rate on the experimental floor.

Bulk Shielding Design

When beam is being delivered to the FEE, the closest areas accessible to personnel are the first experimental beam downbeam of the FEE and the entrance of the access maze.

Table 1: Beam Losses and Associated Bremsstrahlung Power Entering the FEE.

	Loss or rate/charge	**Brem. to FEE**
Collimators	20 W	15 mW
BYD magnet	20 W	37 mW
BFW	120 Hz/1 nC	751 mW
Wire scanner	120 Hz/1 nC	206 mW

The design of the access maze was done using FLUKA by conservatively considering scattered radiation from the spontaneous and bremsstrahlung photons impinging on targets that lead to the highest dose rate at the access maze entrance [6]. The downbeam wall of the FEE, separating the FEE from the first hutch, is made of a 90 cm thick layer of steel followed by 90 cm of concrete. The 30 cm thick steel so-called “shadow wall” shown in Figure 1 is a complement to the FEE downbeam wall. Its objective is to cover a possible weakness in the FEE wall as the steel portion of the wall is not covering the entire first hutch. Calculations have also shown that it attenuates and scatters a significant fraction of secondary radiations generated in the upstream portion of the FEE [7]. The FEE downbeam wall has three holes to accommodate the passage of the beam pipes going from the FEE to the experimental stations. The beam pipes for the two soft X-ray experiments located inside the first two hutches of the NEH go through the two holes with the greatest offset with respect to the electron beam line. The hole with the smaller offset (3 cm) is for the beam pipe leading to one of the hard X-ray experiments located in the NEH or in the FEH. For the design of the downbeam FEE shielding wall, it was assumed that the hutch shutters controlling the beam delivery to the hard X-ray beam line were in an open position as it is envisioned to allow access to the first hutch while the beam goes to downbeam experiments. FLUKA calculations were performed considering the different radiation sources described in the previous section [7, 8]. It was found that the shielding design is driven by penetrating radiation such as neutrons and muons induced by the bremsstrahlung. As an example, the dose rate due to the use of the beam finder wire located before the last undulator is shown on a two dimensional color plot centered on the beam line and covering the downstream portion of the FEE and the first hutch in Figure 2. Contribution to the dose rate of neutrons, gamma and muons were also scored individually. The higher dose rate close to the straight ahead beam pipe is dominated by muons, while neutrons are the main contributors to the dose rate in the rest of the hutch. Considering the use factor of beam finder wires (the highest source of bremsstrahlung as indicated in Table 1) and the power limitations when such devices are used, the downstream wall of the FEE provides sufficient shielding to ensure that the dose to personnel inside the first hutch is well below the design limit of 1 mSv in a year.

Beam Containment System

The BCS is a combination of mechanical devices and associated electronic protection devices that contain the beam within an approved channel and prevent abnormal radiations level in occupied areas. The different collimators along the beam line are part of the BCS as they intercept an important fraction of the bremsstrahlung entering the FEE. An extensive number of studies were performed considering collimator mis-alignment scenarii. It was found that in some extreme cases, a small fraction of the bremsstrahlung could leak into the first hutch through the collimators aperture and generate higer radiation levels [7]. As a consequence, a strong configuration control of collimators (collimators are locked once aligned) and other bremsstrahlung targets is in place. Two pairs of PICs are also located close to collimators to shut-off the beam in case of an abnormal radiation level inside the FEE.

Due to the characteristics of the FEL beam and particularly the high peak photon density and its potential damaging power, special measures were taken to ensure that the FEL beam remains contained within the vacuum hardware. A detailed photon ray trace study taking into account all possible mirror translations and rotations (and thus all possible FEL beam trajectories) was performed in order to determine which were the items fullfilling a BCS function [9]. All components intercepting the beam including elements of the radiation safety systems such as collimators or hutch shutters are protected with a 1 cm thick layer of B_4C. This material has been identified as a good candidate to safely absorb the intense beam thanks to its low atomic number and its high melting temperature [10]. Calculations of the surface dose to B_4C for the different LCLS FEL beam conditions were performed and show, that for normal operation, the temperature increase resulting from the pulse energy deposition in the sample does not exceed the melting temperature of B_4C [10]. In addition, several experiments have been conducted to reproduce surface doses similar to those expected on B_4C exposed to the LCLS FEL beam [11]. However none of those experiments were conducted in a wavelength range characteristics to the LCLS. For that reason, during the commissioning of the FEE, a plan for testing the survivability of B_4C exposed to the LCLS beam was carried out [12]. A B_4C sample remotely monitored with a camera was installed in front of the first beam stopper where the highest photon density is expected. The sample was exposed to more than 9 millions pulses as both the possibility of damages resulting from either a single pulse or multi-pulses were investigated. After the irradiation, the sample was taken out for closer inspection using tactile profilometry and a Scanning Electron Microscope. The analysis concluded that for the irradiation time and conditions the B_4C sample did not experience any FEL beam induced damage.

In order to confirm those results and fully validate the use of B_4C to protect radiation safety items intercepting the beam, it is proposed to conduct material damage ex-

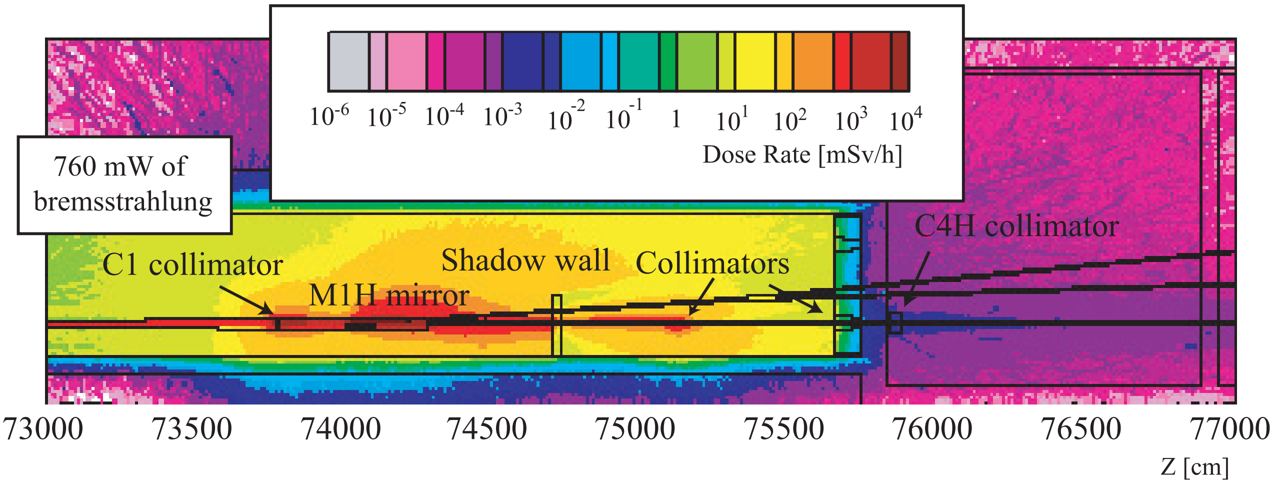

Figure 2: Two dimensional view of the rate inside the FEE and first experimental hutch due to the use of a beam finder wire for the maximum allowed nominal beam power.

periments in the first experimental hutch hosting the AMO instrument [12]. It is planned to use the beam focusing capability of that instrument to reach the surface dose limit above which single pulse damage are observed and thus validate the theoretical model. Multi-pulse experiments below the damage threshold will also be conducted in order to have a better understanding of damage mechanisms.

CONCLUSIONS

The design of the FEE shielding was driven by the high energy bremsstrahlung (several GeV) with the ability of generating very penetrating secondary particles such as neutrons or muons. FLUKA calculations using detailed and realistic description of the geometry and beam losses have been performed to design the shielding of the FEE and investigate the radiological consequences of collimator mis-alignment and other radiation safety system failures. The containment of the FEL beam is based on the use of material (B_4C) with the ability of safely absorbing the intense FEL photons pulse in the hundreds of eV energy range. Due to the unique characteristics of the LCLS FEL beam, the use of B_4C to protect radiation safety item will be experimentally validated whenever the FEL beam performances are enhanced. The use of B_4C will ultimately be validated when beam focusing capability becomes available inside the first hutch and the damage threshold can be experimentally defined.

REFERENCES

[1] W.R. Nelson, T. M. Jenkins, “The SHIELD11 Computer Code”, SLAC Internal Publication, SLAC-Pub-10115, (2005).

[2] N. V. Mokhov, “The MARS Code System User Guide”, Fermilab-FN-628 (1995). CERN-2005-10, (2005).

[3] A. Fassó et al “FLUKA: a multi-particle transport code”, CERN-2005-10, (2005).

[4] M. Santana Leitner et al “Radiation Protection Studies for the LCLS Tune-Up dump” to be published in the proceedings of the 11th International Conference on Radiation Shielding (ICRS-11).

[5] H. D. Nuhn, “Maximum Credible FEL and Spontaneous Energy per Pulse”, LCLS Physics Requirement Document, PRD-1.1-005, (2009).

[6] A. Fassó et al “FLUKA Calculations for LCLS Mazes and Penetrations” SLAC Radiation Physics Note RP-06-09 Rev. 1, (2008).

[7] J. Vollaire et al, “Dose rate in the NEH hutches due to bremsstrahlung entering the Front End Enclosure of the LCLS”, SLAC Radiation Physics Note RP-08-05 (2008).

[8] J. Vollaire et al, “Overview of the Radiation Safety Systems for the operation of the LCLS Front End Enclosure (FEE)”, SLAC Radiation Physics Note RP-09-13, (2009).

[9] P. Stefan, Beam Containment in the Offset Mirror System Region of the LCLS Front End Enclosure, LCLS Engineering Specification Document 1.5-132, (2008).

[10] R. M. Bionta, “Controlling Dose to Low Z Solids at LCLS”, N Division, Physics Dept., LLNL, lcls-tn-003, (2000).

[11] J. Chalupsk et al, “Non-thermal desorption/ablation of molecular solids induced by ultra-short soft x-ray pulses” Optics Express Publication, Vol. 17, No. 1 Pages 208-217, (2008).

[12] S. Moeller, “B_4C test results for Phase 2 and plans for Phase 3” Presentation to SLAC Radiation Safety Commitee, (2009).