

Commissioning of the Electron Line of the Linac Coherent Light Source Dose Rate Measurements and Simulations

M. Santana Leitner¹, J. M. Bauer¹, A. Fassò, J. C. Liu¹, X. C. Mao¹, A. Prinz, S. H. Rokni¹,
T. Sanami^{1,2}, J. Vollaïre¹

¹ SLAC National Accelerator Laboratory, 2575 Sand Hill Rd., Menlo Park, 94085-CA (USA)

² Radiation Science Center, KEK, OHO 1-1, Tsukuba, Ibaraki 305-0801 (JAPAN)

Email contact of main author: msantana@slac.stanford.edu

Abstract. The Linac Coherent Light Source at the SLAC National Accelerator Laboratory (operated by Stanford University for the US Department of Energy) is the world's first hard X-ray Free Electron Laser machine. It uses high energy electrons delivered by a linac to create ultrafast and brilliant X-ray pulses that can be used as a 'high-speed' camera to obtain images of atoms and molecules.

LCLS is a pioneer machine and, as such, its design has encountered unprecedented challenges, the solutions to which will benefit future facilities of its kind across the globe. This article describes the radiation protection aspects of LCLS electron beamlines. Special emphasis is put on the successful commissioning of the LCLS electron line, where, for all examined loss sources, the measured prompt and residual dose rates are in agreement with or below the values predicted through detailed Monte Carlo simulations, used earlier to design the shielding.

1. Introduction

SLAC National Accelerator Laboratory, operated by Stanford University for the US Department of Energy, is now commissioning the Linear Coherent Light Source (LCLS), the world's brightest X-ray machine, which will act as an ultrafast stop-motion camera able to capture snapshots of molecules as they evolve during reactions. LCLS will deliver laser beams for cutting-edge research in a wide variety of scientific domains, including medicine, advanced energy research, femtochemistry, nanoscale dynamics in condensed matter physics and plasma physics, among others [1, 2].

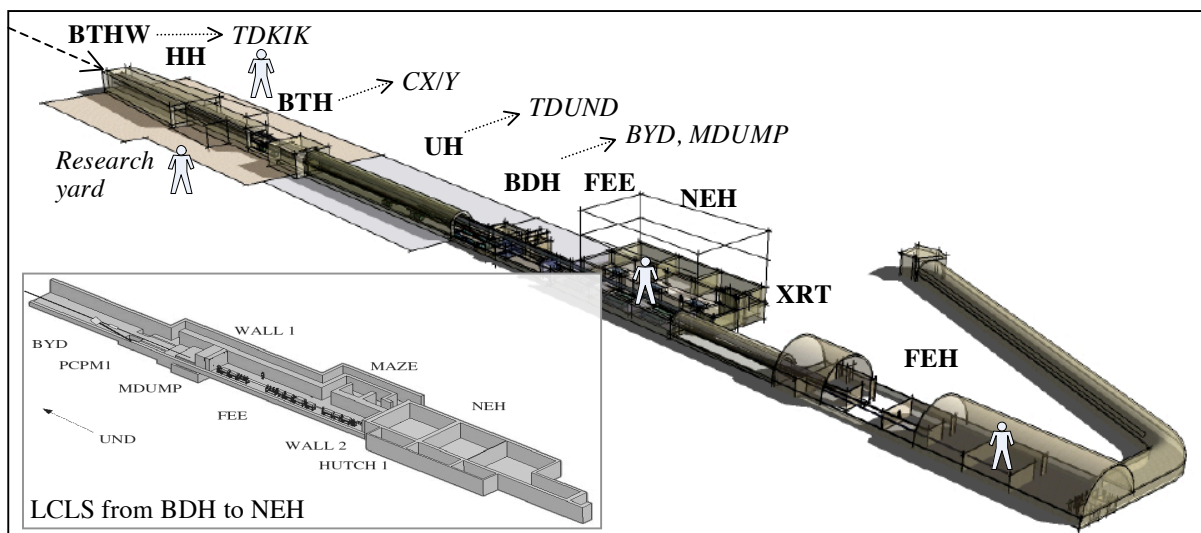


FIG. 1. Scheme of LCLS from the Head House (HH) to the Far Experimental Hall (FEH)

The 420 M\$ LCLS project uses the final third of the SLAC 2-mile linac to accelerate electrons up to 17 GeV, which are then transported through new accelerator buildings (HH-

BTH) towards a long hall (UH) hosting thirty three 3.4 m long undulators where the sinusoidal oscillations of the beam create synchrotron radiation that interferes coherently with the downbeam electrons, leading to an intense sharp Free Electron Laser (FEL). The electron beam is then electromagnetically deflected to a buried dump, while the straight photon pipe crosses a thick shielding wall (WALL1) to reach the Front End Enclosure (FEE). The upstream part of FEE hosts an attenuator system as well as the diagnostics for characterization of the FEL. In the downstream part, a set of six mirrors is used to deliver the beam to three beam lines. The beam lines travel through a second wall (WALL2) into the three consecutive experimental hutches of the so-called Near Experimental Hall (NEH). The higher energy line continues through a long straight section called the X-Ray Transport tunnel (XRT) up to the Far Experimental Hall (FEH), where three more hutches will host instruments for further photon science experiments.

LCLS is a pioneer machine, and, as such, it has faced unique technical and scientific challenges in many domains (alignment, photon science...), including *radiation protection* (RP). In particular, in order to ensure a radiologically safe operation of the LCLS, detailed simulations of the radiation fields were performed, and dedicated radiation measurements carried out during the commissioning of the electron line served to validate the shielding, as well as to tune the safety systems. This paper describes the main radiation protection items for the *electron line* of LCLS, introduces the associated Monte Carlo simulations, summarizes the methodology and results of the surveys performed between December 13th and December 16th 2008, and discusses the accordance of the survey results with the expected values.

As for the *photon lines*, the designs and implementation of the safety systems to transport and contain the powerful FEL are now being tested and will be presented in future publications.

2. Radiation protection studies for LCLS electron lines

Before LCLS commissioning, the SLAC Radiation Physics group conducted numerous studies for the LCLS electron lines, including calculation and mitigation of prompt and residual doses, environmental impact assessments, estimation of the radiation damage to permanent magnets and to electronics, etc. Then, during the commissioning of the electron line, RP measured the *prompt and residual* dose rates of some key components, described in Section 2.2.

2.1. Monte Carlo simulations of LCLS

Over 600 m of LCLS tunnel (From BSY to NEH) were entirely modelled with the intra-nuclear multi-particle Monte Carlo transport code FLUKA [4, 5]. The input file contains a realistic 3-D geometrical description of buildings, walls, mazes, and most beam line components, like electromagnets, collimators, dumps, and the 33 undulators, each of them with all of their magnets (224/undulator) and poles. In order to achieve reliable results of the propagation of the cascades in dumps, collimators and other loss sources, the *magnetic fields* of dipoles and quadrupoles were coded in a source routine that was linked and compiled with the rest of the Monte Carlo. As shown in fig. 2, the code perfectly tracks particles along the beam.

Due to the amount of energy deposited in the main dump and to the challenging 0-degree location of the experimental areas with respect to the electron beam (see explanation in 2.2), the BDH-NEH section was also implemented and run independently with Monte Carlo code

MARS15 [6, 7]. Agreement between FLUKA and MARS15 results gave confidence in the shielding designs for the expected electron beam loss rates. Actual dose rates were then measured during the commissioning.

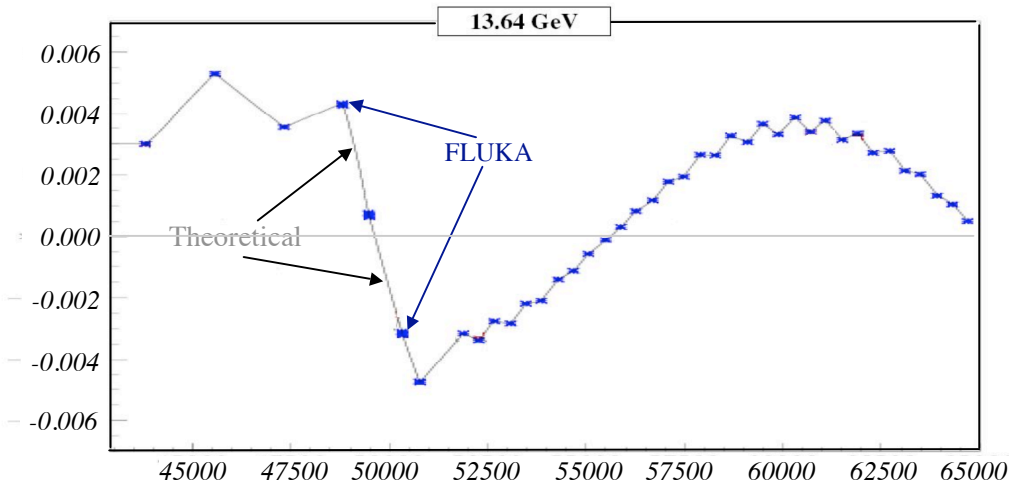


FIG. 2. Comparison of the theoretical and the simulated trajectory along BTH and UH of a 13.6 GeV electron starting at $Z=440$ m (from the so-called ST-100), $Y=30$ μm with $v_x=v_y=0$.

2.1. Radiation hazards of LCLS electron lines

The main sources for **prompt radiation** are the three dumps, followed by the BTMs, collimators and insertable devices.

The electron beam can be prematurely terminated in one of two intermediate **dumps**, either by kicking it off-axis to a collimator-like stopper (TDKIK) located in the BTH west (see figs. 1 and 2), or by inserting a pneumatically actuated stopper (TDUND) into the beam path, just before the undulators. Otherwise, the beam travels all the way through the undulator before it is steered downward into a pit that shields the main dump (MDUMP). Although all three dumps are in underground areas, significant radiation from each of them could reach occupied zones. TDKIK is a few meters *upstream* of the above-ground ‘head-house’ (HH) / BTH building, and therefore the muons generated in TDKIK by the high-energy electrons may get to the *research yard* (space around BTH) in significant amounts. Similarly, TDUND is located shortly *downstream* of the BTH building (thus already inside the UH hill), but back-scattered radiation could reach the service building above the BTH, just facing the hill. Moreover, muons could propagate from TDUND all the way down to the FEE-NEH (occupied areas). Finally, since the Beam Dump Hall (BDH) is past the UH hill the section of BDH at MDUMP was covered by four and a half meters of soil. One of the charges of the commissioning was to verify the adequacy of that amount of soil.

The beamline in BTH has beam optic components, BTM’s and **collimators**, but no dump. Therefore, losses in BTH are expected to be very modest (<20 W total), but since the building crosses the research yard without further soil shielding, thick¹ concrete walls are necessary to limit the lateral radiation.

The same objects that are sources of prompt dose become activated and emit **residual radiation**. The level of that radiation will depend on the local shielding around the object as

¹ 1.8 m thick walls on the sides and in the roof below the three service buildings, 1.2 m in the remaining sections of roof.

well as on the irradiation conditions and the access time and duration. During the commissioning, surveys have been performed around the three dumps and along the entire beamline from BTHW to BDH.

One of the most critical RP challenges was the fact that the occupied areas FEE and NEH are in the (prolongation) line of sight of the main electron beam, located downstream of MDUMP, to which the electrons are steered by electromagnets (BYD). This set of magnets shares a power supply with an earlier chicane so that, in case of power failure or polarity inversion, the beam would not make it through the chicane and it would therefore not reach FEE regardless of BYD magnet status. As an additional layer of safety towards avoiding electrons reaching FEE, three permanent magnets (PM1-3), located downstream of BYD but before the FEE wall, would kick the electron beam to a side dump (SDUMP), and two protection ion chambers (PIC) would trigger a beam shut off. A secondary hazard linked to the direct downbeam position of the occupied areas is the fact that inserted diagnostics and shallow beam losses (e.g. in BYD) create **bremstrahlung** photons that point directly at FEE. Unlike the FEL, those undesired photons do not have the right wavelength to be directly conducted by the FEL mirrors into the (occupied) NEH, but, instead, they create showers in those mirrors (and in other components) that could ultimately propagate through WALL2 into NEH. These complex and critical situations are hard to compute by analytic means. Consequently, the design of WALL1 and WALL2 was based on the results of two independent sets of simulations performed with two state-of-the-art Monte Carlo transport codes. Those results were checked for consistency and were compared to the measurements obtained during the commissioning of the electron line of LCLS.

3. Commissioning measurements

3.1. Instrumentation

The *prompt radiation* was measured with portable survey meters and with four so-called ‘BF3/GM stations’. The portable instruments used to measure photons were *Bicron Microrem* meters (plastic scintillators), while HPI 5085 *Meridian* and *Eberline ASP-1* with NRD served to measure neutrons. The movable BF3/GM include a BF₃ neutron detector and a Geiger Mueller N-114. For dose rate measurements in FEE, two BF3 stations were installed behind WALL1, one below the existing beam line and the other one below the future north line. For measurements in BTH, one BF3 station was used for the north side and another one for the south side.

The *residual radiation* was measured with *Eberline ASP-1 & ASP-2* with HP 270 (GM) probe and with *Victoreen 450* ion chambers².

3.2. Miscellaneous considerations

- 1) LCLS runs from West to East. The elements to the *right* of the beam are thus often referred as to the *south*. Those to the *left* are also labelled as to the *north*. The *z* axis is oriented with the beam, *x* points upwards and *y* aims at the south.
- 2) The LCLS tunnel has been designed to eventually host two parallel beam lines, equidistant to the tunnel central plane. Presently there’s only the south beam line.

² The residual contamination was evaluated with the *Technical Associates TBM 15*, equipped with a GM pancake detector and the *Ludlum Model 3030*. No contamination was observed.

- 3) The sequence of sections of LCLS is: LINAC → BSY → BTHW → (HH) + BTH → UH → BDH → FEE → NEH → XRT → FEH
- 4) The north and south sides of the HH diverge to accommodate eventual sidelines into the research yard. The two exits are presently plugged by heavy shielding blocks in order to attenuate muon fluxes that are generated when the beam is kicked to TDKIK.
- 5) The nominal energy of LCLS ranges from 4 to 17 GeV.
- 6) The maximum beam power for the current line is 2.0 kW (nominal is 1.7 kW). The maximum overall power is 5 kW. Lower power was used during commissioning.
- 7) The maximum allowable dose rate for areas accessible to general public (e.g. NEH) is $0.5 \mu\text{Sv/h}$ (1 mSv/y), and $5 \mu\text{Sv/h}$ (10 mSv/y) for other zones (FEE, access to LCLS tunnel...).

3.3. Prompt dose measurements

For beams up to TDUND, the prompt radiation was measured for losses in collimators (5 W), BTM's (10 W) and tune-up dumps (300 W at TDKIK, 100 W at TDUND). Measurements were performed outside the accelerator building HH/BTH, in the upper service buildings, penetrations, and mazes. Moreover, when the beam was parked on TDUND, the prompt dose was also measured behind WALL1.

For beams up to MDUMP (300 W in MDUMP or 10 W mis-steered in BYD), prompt dose measurements were performed in FEE (and NEH), above MDUMP and at the exit of shafts and penetrations.

Prompt dose from the electron dumps: TDKIK, TDUND and MDUMP

With 300 W (13.6 GeV) electrons kicked to **TDKIK**, survey meters placed behind HH end plugs did not measure any neutrons (as expected) but counted photons (presumably muons). The experimental dose rates, rescaled to 2 kW, are $2 \mu\text{Sv/h}$ in the north side and $1 \mu\text{Sv/h}$ in the south side, both below $5 \mu\text{Sv/h}$ and in good agreement with simulations, shown in fig 3. In case of a second beam line with a similar dump and shielding, the maximum dose from the combined sources (4 kW in total) would be $3 \mu\text{Sv/h}$ for both the north and south plugs.

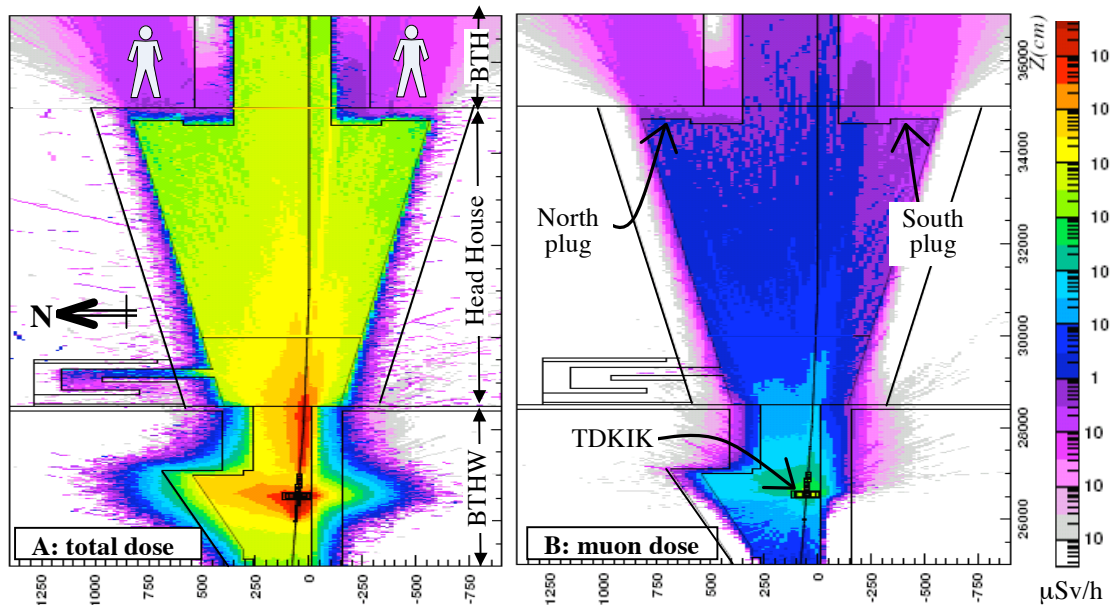


FIG. 3. Top view (at beam plane) of the total and muon dose rate [$\mu\text{Sv/h}$] around HH when 2 kW, 13.6 GeV electrons are kicked to TDKIK. Commissioning measurements were taken behind the end plugs.

For 100 W (13.6 GeV) dumped onto **TDUND**, the small expected levels of backscattered radiation towards open or occupied areas were undetected. As for the forward dose to the FEE, which FLUKA had estimated to range from 0.05 to 0.06 $\mu\text{Sv/h}$, the two GM probes stationed behind WALL1 measured photon (muon) doses of 0.051 $\mu\text{Sv/h}$ and 0.058 $\mu\text{Sv/h}$, respectively. The readings are similar because the detectors are very close to each other (~ 2 m), while the loss point is relatively far (220 m). The dose rate scaled to 170 W would still remain well below the design limit.

For 13.6 GeV onto MDUMP, the dose rate measured behind FEE WALL1 on the south beam line, scaled from 300 W to 2 kW was ~ 0.10 $\mu\text{Sv/h}$. The corresponding dose computed [7] with FLUKA at 17.0 GeV ranges (statistical uncertainty) from 0.04 to 0.10 $\mu\text{Sv/h}$. The measured dose in FEE (at beam height and near the south end plug), once scaled to 2 kW, would be 0.1 $\mu\text{Sv/h}$. The BF3/GM station located behind the north beamline wall plug was unable to measure any radiation, as predicted with FLUKA. As for lateral prompt dose escaping MDUMP to the upper road above the dump hall, the hand-held instruments were unable to detect the low expected dose rate values (~ 0.01 $\mu\text{Sv/h}$). Further measurements will be carried out once the maximum power is achieved. During the commissioning the beam was parked on TDUND and MDUMP on several occasions. Although faint, each time that the beam was parked on either of these dumps, the BF3/GM units were able to read signals.

Lateral dose from small beam losses along BTH

A series of measurements was performed for 5 W-13.6 GeV beams intercepted by **collimators** at different BTH locations. RP had marked the Z-location of the collimators in the exterior surfaces of the north and south walls of BTH. The BF3/GM stations were placed near the marks and survey meters were used to verify the right location. Total dose rates measured by BF3 stations and survey meters on the south wall near each collimator ranged from 0.3 to 0.7 $\mu\text{Sv/h}$, with a neutron to photon dose rate ratio of about 3. Results on the north side were 30 to 40 % lower than on the south side because the current beam line is closer to the south wall. The doses are safely below the 5 $\mu\text{Sv/h}$ shielding design limit, which had been calculated for a generic thick target, and without taking into account the additional attenuation provided by the massive steel bar structure embedded in the concrete walls of the BTH.

Bremsstrahlung losses in BDH

The beam was **mis-steered in BYD** (10 W loss at 13.6 GeV) with several directions (up, down and to the north side). Both stations at FEE measured highest dose rates during upwards mis-steering, with ~ 0.2 $\mu\text{Sv/h}$ muon and 0.1 $\mu\text{Sv/h}$ neutron doses. These numbers are comparable to the corresponding Monte Carlo estimations for the total dose, ~ 0.15 $\mu\text{Sv/h}$ (FLUKA) [8] and ~ 0.5 $\mu\text{Sv/h}$ (MARS). In order to identify possible detector dead-time effects, the measurement was performed at 1 Hz and 10 Hz, with identical results. Similar tests were performed for collimators close to BYD.

Finally, a 10 W beam was steered upwards by a corrector magnet halfway **between BYD and MDUMP**. A jet of muons in the south beam plane at about 40 cm from the floor was readily measured both with portable survey meters and BF3/GM station. The GM detector measured 0.2 $\mu\text{Sv/h}$ at 1 m of height and 0.5 $\mu\text{Sv/h}$ (muons) at 40 cm from the floor. The neutron dose was ~ 0.1 $\mu\text{Sv/h}$, roughly uniformly behind WALL1.

3.4. Residual dose measurements (limit is $5 \mu\text{Sv/h}$)

The dose measured in the aisle, 30 cm from **TDKIK** after 1 h irradiation (300 W) and 3 h cooling was $0.2 \mu\text{Sv/h}$ (thus $\sim 1.3 \mu\text{Sv/h}$ for 2 kW). Hot spots were found in the front and back faces of the dump around the pipe. These measurements are compatible with simulations. Typical residual doses measured for **collimators** that had been used as 5 W targets were of the order of $2 \mu\text{Sv/h}$. RFBPM7 (a few feet upstream of TDUND) registered higher (though short-lived) residual dose rates $\sim 0.14 \text{ mSv/h}$.

TDUND was irradiated for 1 h at 100 W (13.6 GeV), and the residual radiation was measured shortly after (10 min), see fig. 4 below. The dose rate at 30 cm from the lateral shielding (a 15 cm thick marble plate) was $1 \mu\text{Sv/h}$. This value is comparable with the Monte Carlo prediction of $5 \mu\text{Sv/h}$ for 2 h irradiation at 170 W.

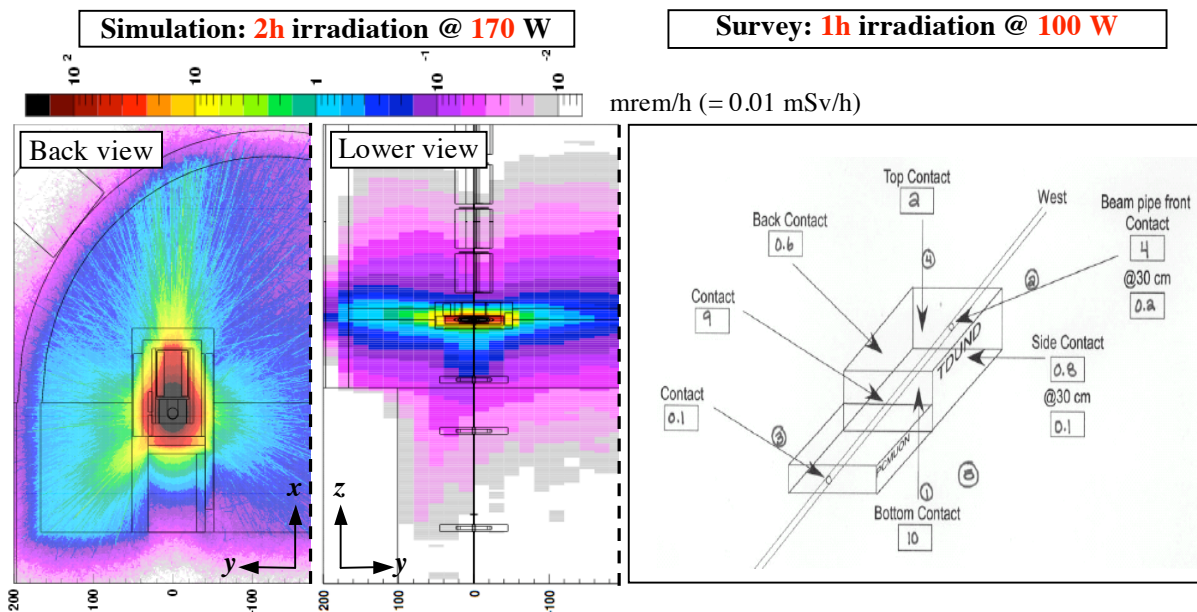


FIG. 4. Monte Carlo downstream and underside residual dose rate maps around TDUND (2h irradiation at 170 W) and experimental survey (1h irradiation at 100 W). Cool down time was 10 min.

The residual dose rates measured above the plates that cover MDUMP pit after a few hours of irradiation at 100 W were on the order of $1 \mu\text{Sv/h}$. The dose in the front crack between the covering plates and the concrete reached $8 \mu\text{Sv/h}$, while the dose rate upstream of the dump pit was $\sim 5 \mu\text{Sv/h}$.

3. Conclusions and final remarks

Additional areas were surveyed (e.g. leakage through penetrations, or mazes) and some other loss sources not covered in this note were induced. Moreover, simulations had investigated many other scenarios that have not yet been surveyed experimentally. When the beam power will be raised, it will be a good chance to repeat some measurements and perform new ones. In all measurements, the prompt and residual dose rates stayed below the shielding design limits and generally remained within a factor 2 or less (typically 30% up or down) of the Monte Carlo calculations.

Acknowledgments

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