

Radiological Studies for the LCLS Beam Abort System

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The Linac Coherent Light Source (LCLS), a pioneer hard x-ray free electron laser is currently under construction at the Stanford Linear Accelerator Center. It is expected that by 2009 LCLS will deliver laser pulses of unprecedented brightness and short length, which will be used in several forefront research applications. This ambitious project encompasses major design challenges to the radiation protection like the numerous sources and the number of surveyed objects. In order to sort those, the showers from various loss sources have been tracked along a detailed model covering 1/2 mile of LCLS accelerator by means of the Monte Carlo intra nuclear cascade codes FLUKA and MARS15.

This article covers the FLUKA studies of heat load; prompt and residual dose and environmental impact for the LCLS beam abort system.

Key Words: thermal load, radiation shielding, accelerator shielding, residual radiation, groundwater activation, tritium, ^{22}Na , beam dump.

Introduction

This work contains most of the studies required for the radiation design and approval of a beam dump. First the integrity of the dump when the beam is fully dumped at 5 kW, 120 Hz and 17 GeV is verified through Monte Carlo Simulations of the heat load. Then a lateral shielding is designed to minimize the residual dose rate around *tdkik*. Activation and gamma decay are fully integrated in a single simulation run. Next, with the lateral shielding in place and with a set of lead blocks that shield for low angle muons, the prompt dose downstream *tdkik* is computed. Finally, the groundwater activation has been calculated, in particular, the peak concentrations of ^3H and ^{22}Na have been estimated.

All these calculations have been performed with FLUKA, a powerful **Monte Carlo** intra nuclear cascade code that is able to cope with the coupled transport of electrons and neutrons, and which is capable of performing both prompt dose and activation studies. Photonuclear and photomuon reactions have been

turned on, and conversion functions [3,4] have been used to obtain the radiation dose equivalent. Subroutines have been modified to compute the peak temperature rise from the density of energy which is typically provided by the code.

Single Beam dumper

A pulsed dipole magnet and dump (*tdkik*) placed at the Beam Transfer Hall West (BTHW) of the LCLS will rapidly stop or lower the beam intensity during invasive tuning sessions, when the downstream undulator could be damaged by the mis-steered poor quality beam. The beam abort system rapidly deflects the beam vertically (~ 1 mradian) so that the electrons no longer go through the *tdkik* central hole. Instead they collide in the copper, 1.2 cm below the orbit. In order to dilute the local heat density in the *tdkik* a thin (1 mm) spoiler of $\text{Ti}_6\text{Al}_4\text{V}$ is inserted to disperse the beam. The 5 kW, 17 GeV electron beam stopped in *tdkik* generates showers that are partially self-shielded by the *tdkik* and by a set of four consecutive collimator stoppers placed down-beam (*pctdkik1-4*).

The spoiler, *tdkik*, *pctdkik* stoppers as well the QDL23, QT21 and QT22 quadrupoles are aligned in the long beam section of the dogleg that forms a 1° horizontal angle with the reference axis. In order to perform the calculations, the implemented model of LCLS was enlarged to include the BTHW and Head-house sections with its relevant elements: spoiler, beam dumper, shieldings, beam pipe and magnetic fields in the dipoles of the dogleg and in the over-mentioned quadrupoles.

Muon shielding

The *PCtdkik* are blocks ($L = 81.28$ cm, Area = 12.7×12.7 cm²) of lead each of which is contained in a steel casing of 6.35 mm thickness. These blocks have a hole of 1 inch diameter through which the beam travels without interference during normal operation. When the beam is aborted the forward showers coming from *tdkik* (mainly muons), are to be mitigated by this set of zero-degree shieldings.

Lateral shielding

The conceptual shielding around *tdkik* has 5 components:

The **first part** is the outer layer of *tdkik* itself, starting approximately at radius 7 cm and ending at radius 12.3 cm. Initially the self-shielding material was stainless steel, but later on simulations proved that replacing this material by 5%-borated polyethylene helped reduce the residual dose. This is so because when stainless-steel is irradiated by the electron beam or by its showers, photo-neutrons are created and these ultimately activate the surroundings. The mass of this component is 14 kg, 100 kg lighter than the stainless steel version.

The **second component** is a polyethylene block around *tdkik*, 50 cm tall, 118 cm wide and 117 cm of long. A radial clearance around the beam axis of 4.75 cm allows fitting the beam pipe and the corresponding connecting bellows. The mission of this shielding is to thermalize and absorb the photoneutrons. Tests with metals failed to reduce the residual dose rate and resulted in a very heavy shielding. This component can be implemented as slabs, blocks, etc, as long as no major cracks are aligned from the target to the outer faces. The estimated weight for this component is 555 kg.

The **third component** is a large marble parallelepiped around the second component where the marble faces range from 3 to 10 cm. The 0-degree shielding protrudes the downstream marble face. This shield blocks most of the decay gammas emitted by the activated *tdkik* and by the first layers of surrounding shielding. The estimated weight is 625 kg.

The **fourth component** is a 13 cm thick marble plate (360 kg) attached to the aisle side of the third component (also marble). The mission of this component is to further shield the aisle from the photon radiation coming from *tdkik* and from its shielding.

The **fifth component** of the shielding comprises several items in the support for *tdkik*, like a 4 cm polyethylene layer, 10 cm marble faces in the front, back and aisle side and the concrete pillar itself. The total mass of the shielding (concrete support and steel plate not included) is 2376 kg (1770 kg of marble and 606 kg of polyethylene).

Heat load calculations

Monte Carlo simulations of the heat deposited in *tdkik* have been carried with and without spoiler, in order to determine the importance of this device for the heat density in the *tdkik*. Figure 8(b) shows the temperature rise for the two situations. The peak values are 1.9 and 11.0 K, respectively and are registered at about 11 mm below the beam axis. These values are well below the numbers obtained in other stoppers and dumps of LCLS, where stress calculations proved that the objects could sustain the heat load.

Therefore no further stress analysis is needed in this case to certify that the single beam dumper will resist the heat deposition.

Dose Rate Calculations

Residual dose calculations

When the beam impinges onto *tdkik*, muons are created and propagated in the forward direction and rather isotropic neutrons are generated through photonuclear reactions. The first group is shielded with the so-called 0-degree shielding, made of a heavy-Z material, while the latter are moderated in light-Z material around the shielding, with high absorption cross section. The lateral shielding gets activated during the absorption of the energy carried by the neutrons. A fraction of the created radioisotopes decay emitting gammas, which penetrate through the remaining shielding and generate a residual activity dose to the outside¹. In order to shield from the activated shielding and from *tdkik*, marble plates should wrap the neutron shielding. Marble is an extremely pure mineral with sufficiently high density to shield gammas and with the smallest own residual radioactivity [5]².

The resulting residual dose rates [mrem/h] for cooling times ranging from 5 seconds to 1 year, and after a continuous irradiation of electrons at 2 kW, 17 GeV (120 Hz) and for 200 days are presented in figures 1 and 2 (views from below) and 3 ($Z = 26525$ cm cross sections).

¹ Without the shielding, the neutrons would be absorbed in the tunnel and the concrete would get activated. The residual activity would be huge due to ²²Na and ²⁴Na gamma-rays from the walls and from the unshielded activity coming from *tdkik* itself

Looking at those plots, it is seen that the exclusion area below 5 [mrem/h] for the first two cooling times (5 s and 1 minute) doesn't leave a passage alley along *tdkik*. However, after 30 minutes, the exclusion area shrinks notably, leaving a space of about 2 meters between the wall of the triangular wall and the (north) border of the exclusion area. In the residual dose plots it is also observed how a big fraction of the residual dose exits from the front end. For this reason the shielding plug in the front was extended twice until reaching the present configuration. Further extensions could still be considered. However, from the Z-plots we see that most of the dose is actually leaking from the top of the shielding, where no further shielding can be added because space is needed for the upper crane. If this restriction disappeared, then it would be advisable to add some more shielding on top of *tdkik*.

Prompt dose calculations

When the beam impinges onto *tdkik* high radiation levels are generated around the dump, but also a forward peaked component (mainly due to muons) is propagated in the direction of the beam reaching beyond the head-house out of the tunnel.

The single beam dump is located in BTHW, which is a section of the tunnel buried underground. During operation occupancy will not be allowed close to *tdkik* and therefore the main concern associated with the *prompt* dose leakage beyond the concrete walls is the production of ^3H and ^{22}Na in the soil surrounding the tunnel. However the dimensions and materials that are required to shield *tdkik* are dictated by the *residual* dose rate levels.

From figure 4 it is observed how the lateral shielding greatly reduces the dose in inner surface the concrete tunnel, and specially the neutron dose, which will in turn lower the residual dose in the tunnel. The prompt dose in the soil below the tunnel decreases significantly while that to the right of *tdkik* is just 2 to 3 times lower. The dose outside *tdkik* is strongly dominated by the neutrons generated in photonuclear reactions in the dump, as seen in figure 4.

² Calcium has a low massic number A=42 and is a double magic nuclei.

Groundwater activation

The following steps describe the process to determine the maximum use factor (or maximum average power onto *tdkik* in terms of radioisotope production in the groundwater.

FLUKA was run to compute the production of radio nuclei. In particular, two boxes, below and to the wall side of *tdkik* were defined to monitor the production of ^3H and ^{22}Na , among others. The production in the lower box was found to be 5 to 10 times lower than in the side box, where the corresponding production rates were $3.25\text{E-}12$ ^3He -atoms/electron³ and $\sim 1\text{E-}10$ ^{22}Na -atoms/electron. For the 2 kW beam the *saturation activities in soil* ($A_s(\text{soil})$) would be 65250 and 20000 pCi/dm³(soil), respectively.

To evaluate potential environmental impact, it is conservatively assumed that the radioisotopes in soil are leached into groundwater. The efficiency (ϵ) of water to wash off the radioisotopes is taken as 100 % for ^3H and 10 % for ^{22}Na . The corresponding isotope densities in water are therefore amplified inversely proportional to the relative water concentration in the soil (RC_{water}). The **leaching factor** (f_l) is:

$$f_l = \frac{A_s(H_2O)}{A_s(\text{soil})} = \frac{1}{RC_{H_2O}} \cdot \epsilon$$

The maximum spot of irradiation for lateral samples is found at the z location of *tdkik*, where the nearest soil is at a distance of about $d_0=2$ m from the source (*tdkik*). The groundwater at SLAC flows with a speed of about 1 [m/y], meaning that any given volume of water is exposed to the maximum flux of neutrons only for about 1 year, and consequently the activity will not reach saturation even after a long time. Thus the corresponding evolution for the radioisotopes in any slice of a water column flowing at the beam plane⁴ corresponds to the following equation:

$$\frac{dN}{dt} = A_s \cdot f(d) - \lambda \cdot N$$

Where:

- A_s is the saturation activity (obtained in the Monte Carlo simulation).

³ This number already includes a 2.5 factor to correct the known underestimation of tritium production with FLUKA

- The solid angle factor is:

$$f(d) = \frac{d_0^2}{d^2} = \frac{d_0^2}{d_0^2 + (v \cdot t)^2}$$

- t is the time in years.
- v is the sliding speed [m/year], for SLAC $v = [m/year]$

If we consider a time interval of $\pm[y]$ around the moment when the sample is at $d=d_0$, then the corresponding **flow factor** (f_{flow}) will be:

$$f_{flow} = \frac{A_m}{A_s} \simeq \cdot (1 - e^{-\lambda}) \cdot e^{-m\lambda} \cdot \left[1 + 2 \sum_{n=1}^m \frac{d_0^2}{d_n^2} \cdot \cosh(n\lambda) \right]$$

For ^3H the flow factor for $m=0$ ⁵ to $m=7$ are: 0.0548, 0.0932, 0.1372, 0.1583, 0.1674, 0.1699, 0.1687 and 0.1654. We observe that until $m=5$ (11 years of irradiation, 5 before maximum and 5 after) the activation grows due to the increased number of irradiation time. After $m=5$ the activation starts to become lower because the decay losses are larger than the contribution from the additional irradiation time, which starts to become small due to the increased distance with respect to *tdkik*.

Thus the maximum build up is obtained when we consider an interval of $\pm/5$ years, in which case the flow factor is $f_{flow}(^3\text{H})=0.17$.

For ^{22}Na the flow factor peaks at an interval of $\pm/2$ years, and the value is $f_{flow}(^{22}\text{Na})=0.39$ ⁶

A last factor to consider is the volume of the sample. Typically a volume of 1 m^3 is considered representative. In the Monte Carlo simulations only the first 40 cm perpendicular to the wall have been accounted. A **transverse reduction factor** (f_{depth}) has to be applied for a larger sample, as a strong gradient of neutron fluence happens in the transverse direction. The neutron fluence is reduced by about a

⁴ Considering a flow tangential to the tunnel, as it cannot be perpendicular.

⁵ This would only consider one year of irradiation and at d_0

⁶ If the flow speed was reduced to 0.5 [m/y] the corresponding flow factors would increase to 0.27 and 0.53, respectively, thus 59 % and 35 % higher than for 1.0 [m/s]. If, in turn, the flow speed would increase to 2.0 [m/y], the flow factors would be reduced to 0.1 and 0.27 (from 0.17 and 0.39).

factor 2 every 30 cm of penetration into the soil. This means that the average production for 1 m ($A_s(100\text{ cm})$) depth will be approximately:

$$f_{depth} = \frac{A_s(100\text{ cm})}{A_s(40\text{ cm})} \simeq \frac{1 + \frac{1}{2} + \frac{1}{4}}{3} = 0.58$$

Applying all the factors to the computed specific activities in soil, we get the peak specific activity in groundwater (A_{water}). The corresponding limits (A_L) *in water* are 20000 and 400 pCi/l.

For ^3H the ratio specific activity versus limit is:

$$\frac{A_{water}(^3\text{H})}{A_L(^3\text{H})} = \frac{62550}{20000} \cdot \left(\frac{1}{0.2} \cdot 1.0\right) \cdot 0.17 \cdot 0.58 = 1.54$$

And for ^{22}Na :

$$\frac{A_{water}(^{22}\text{Na})}{A_L(^{22}\text{Na})} = \frac{20000}{400} \cdot \left(\frac{1}{0.2} \cdot 0.1\right) \cdot 0.39 \cdot 0.58 = 5.66$$

The previous calculations don't consider any dilution and take into account the conservative leaching assumption. The limiting factor is ^{22}Na production, which dictates the maximum use of *tdkik* to $\text{DF} = 1/5.66 = 18\%$. In terms of ^3H production, the maximum duty factor would be $\text{DF} = 1/1.54 = 65\%$. Moreover, a higher duty factor can be accepted if the power is reduced equivalently. These results do not appear to constrain much LCLS operation, as the predicted duty factor for *tdkik* is between 0.1 and 1%.

Future calculations, air and water activation

Future FLUKA simulations will compute the production of noxious radioisotopes in the cooling water and in the air. The activity from airborne activation will be added to the residual dose rate presented in this paper.

Conclusion and Status of TDKIK simulations

The design of the lateral and forward shielding are adequate to attenuate the residual and the prompt dose, respectively. Moreover, *tdkik* can be used well above the expected 1 % duty factor before the radioisotope production in the surrounding groundwater becomes a concern. Present studies evaluate the activation of air and of cooling water.

ACKNOWLEDGMENTS

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Figure 1: Bottom view of the residual dose rate [mrem/h] around *tdkik* for an irradiation of electrons at 2 kW, 17 GeV, 120 Hz during 200 days and after several cooling times.

Figure 2: Same as figure 1 for longer cooling times.

Figure 3: Cross section of the residual dose rate for several short cooling times.

Figure 4: Cross section of the prompt dose with and without lateral shielding.

Figure 5: FLUKA model of the spoiler and cross section of the heat deposition in *tdkik* with and without spoiler.

Figure 6: Cross section maps of the main components of the prompt dose around *tdkik*.

Figure 7: Plain maps of the prompt dose from *tdkik* downstream, with and without lateral shielding.

Figure 8: Design of the lateral shielding around *tdkik*.

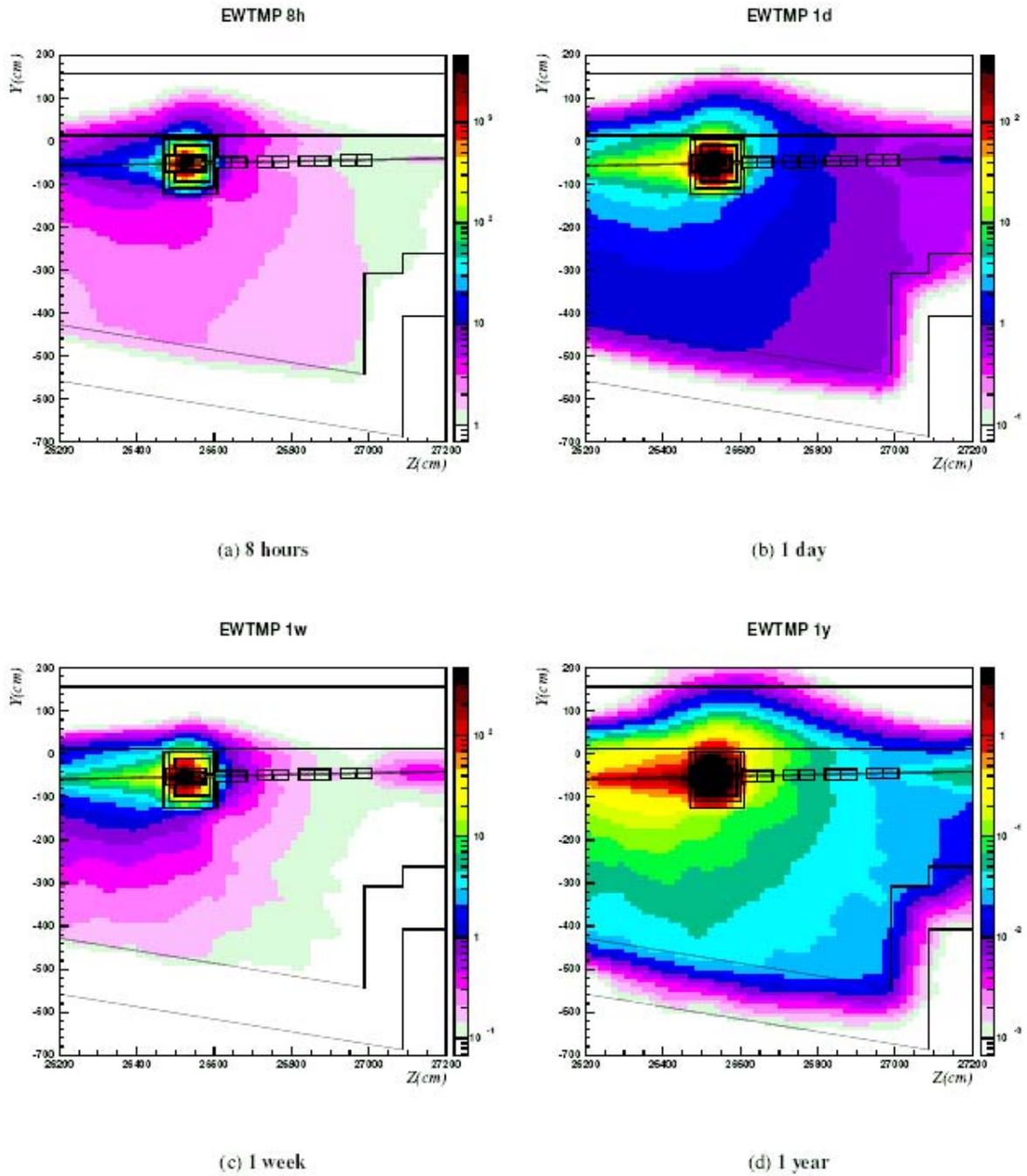


Figure 11: **II. Bottom** view of the residual dose rate [mrem/h] around *tdkik* for an irradiation of e^- at 2 kW, 17 GeV, 120 Hz during 200 days and after cooling times 8 h, 1 day, 1 week, 1 year. Note the change of scale for the last two cooling times.

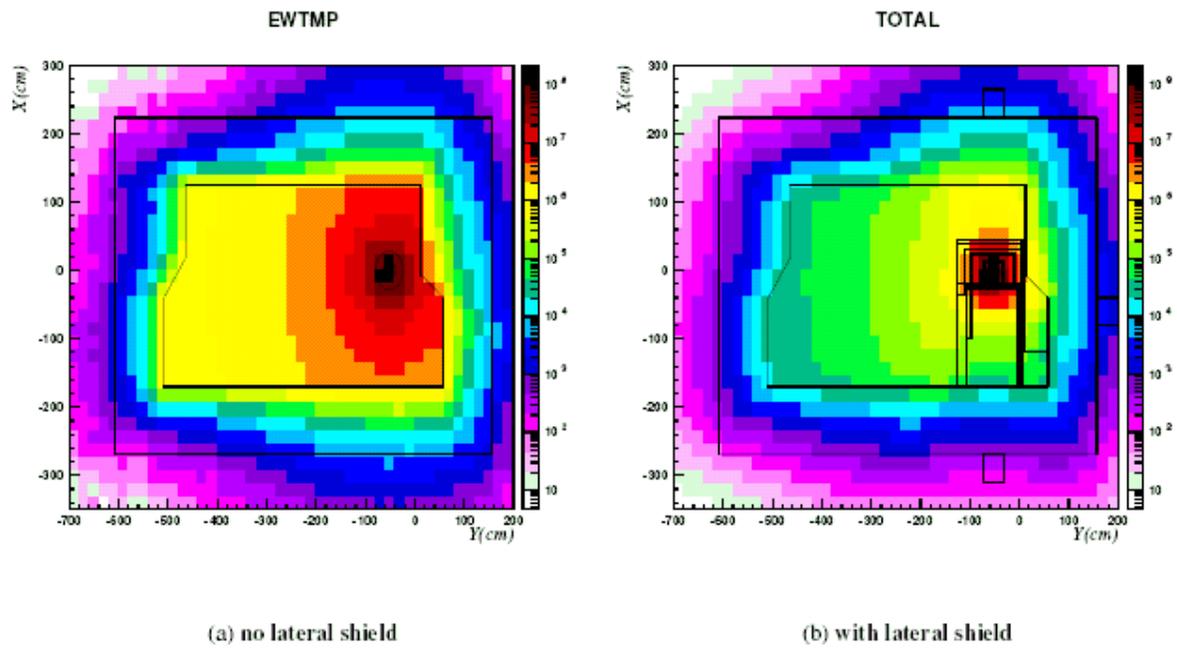


Figure 4 Total prompt dose [mrem/h] for 5 kW of e^- at 17 GeV, 120 Hz dumped onto *tdkik*, a) without lateral shielding or b) with lateral shielding.

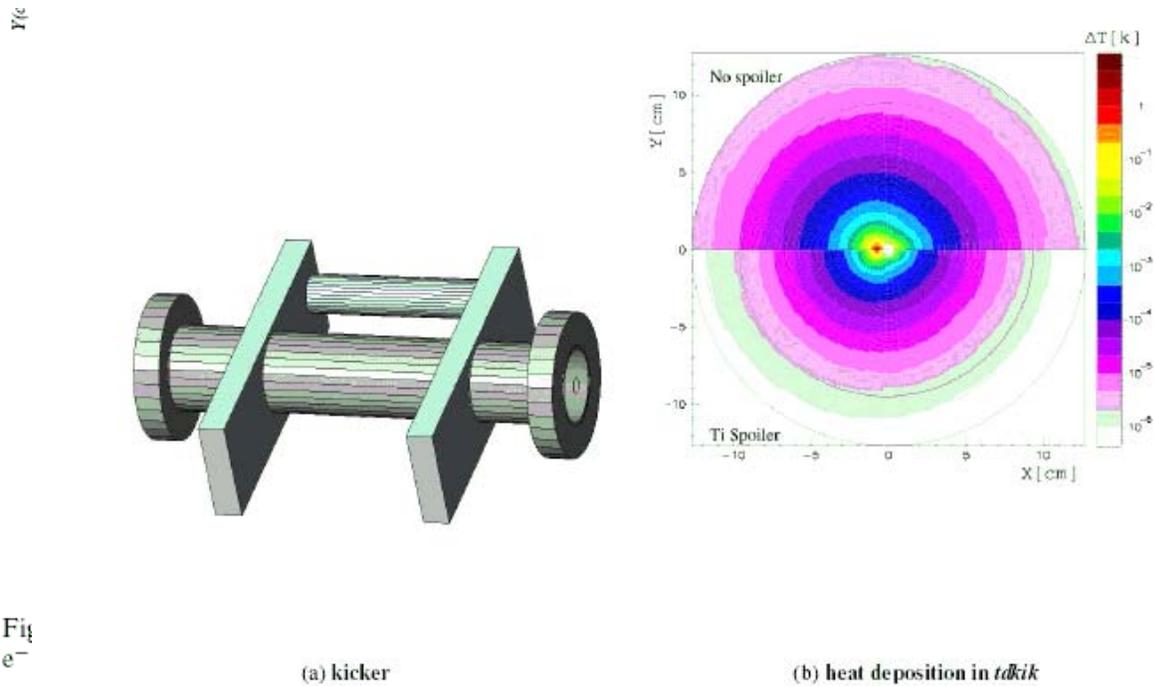


Figure 5 a) Beam kicker as implemented in FLUKA and b) resulting temperature rise [K] in *tdkik* when the spoiler is out (upper half) or in (lower half)

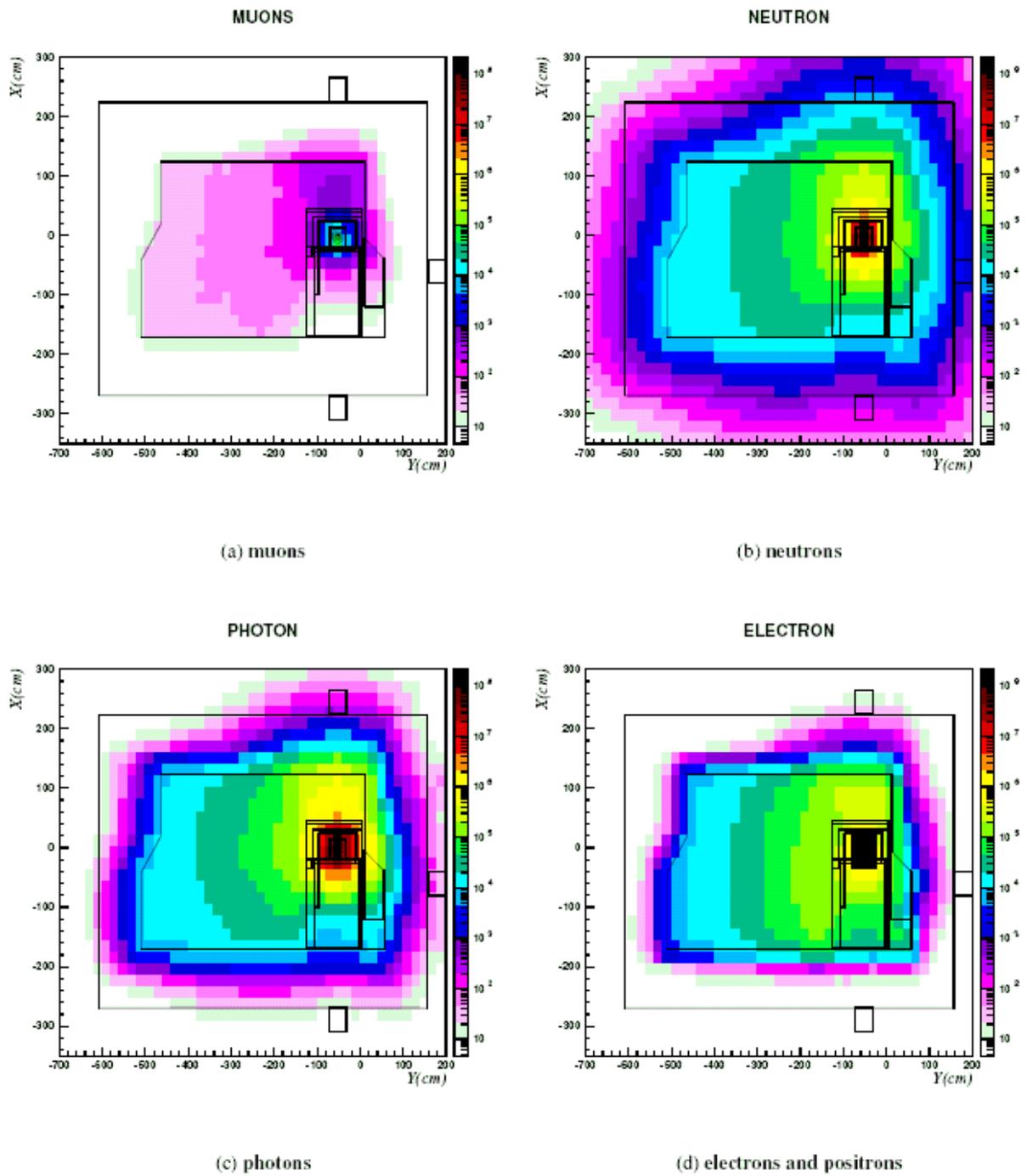


Figure -6 Components of the prompt radiation field [$mrem/h$] for 5 kW e^- , 17 GeV, 120 Hz dumped onto *tdkik*, with lateral shielding.

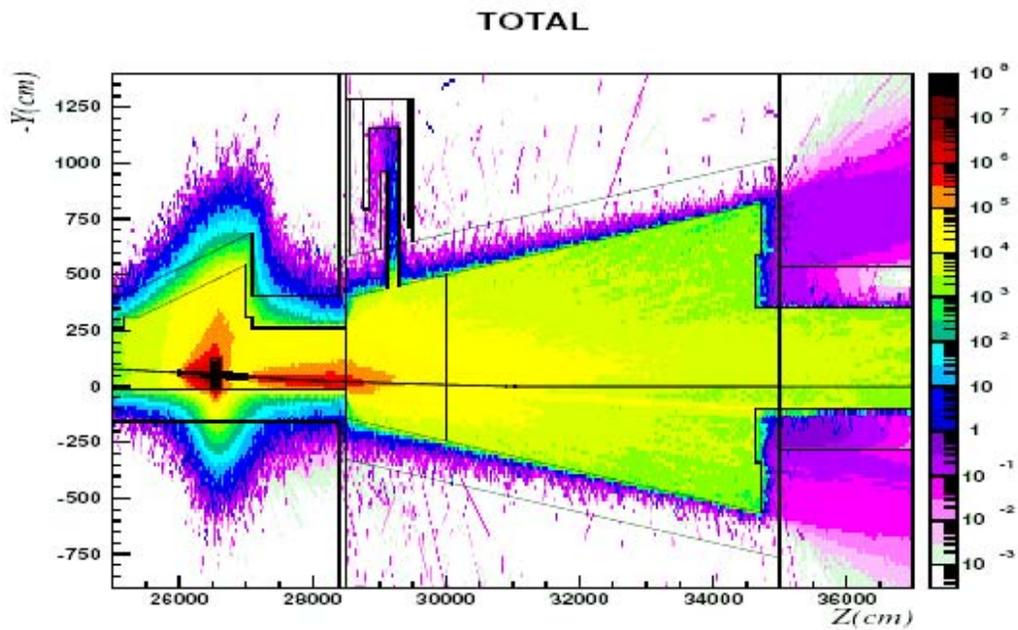
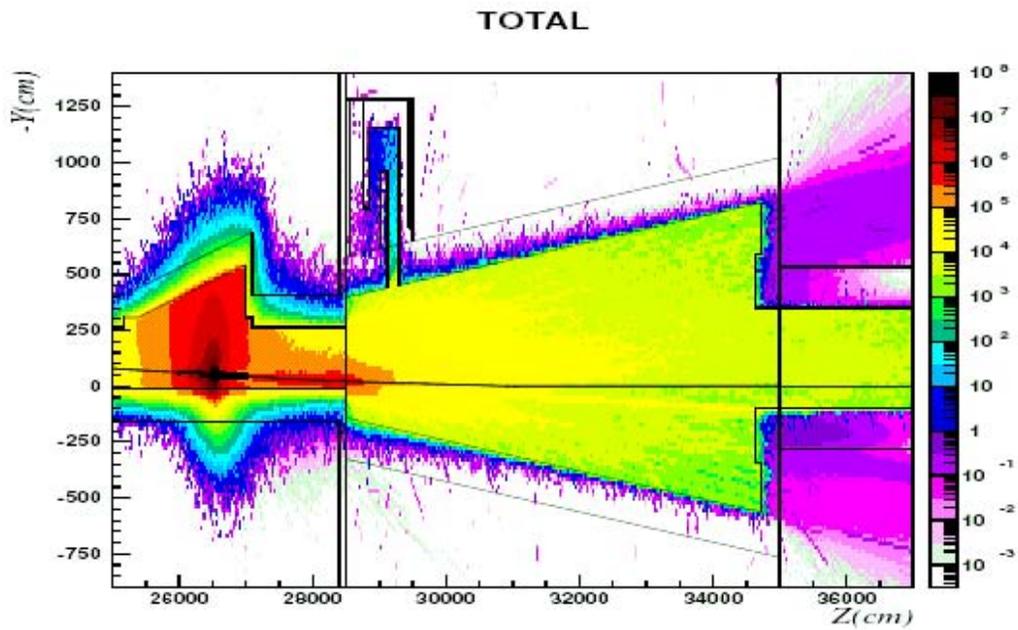


Figure 7 Top view of the total prompt dose [mrem/h] when 5 kW e^- at 17 GeV-120 Hz are dumped onto *tdkik* without (left) and with (right) lateral shielding but always with the 0-degree shielding.

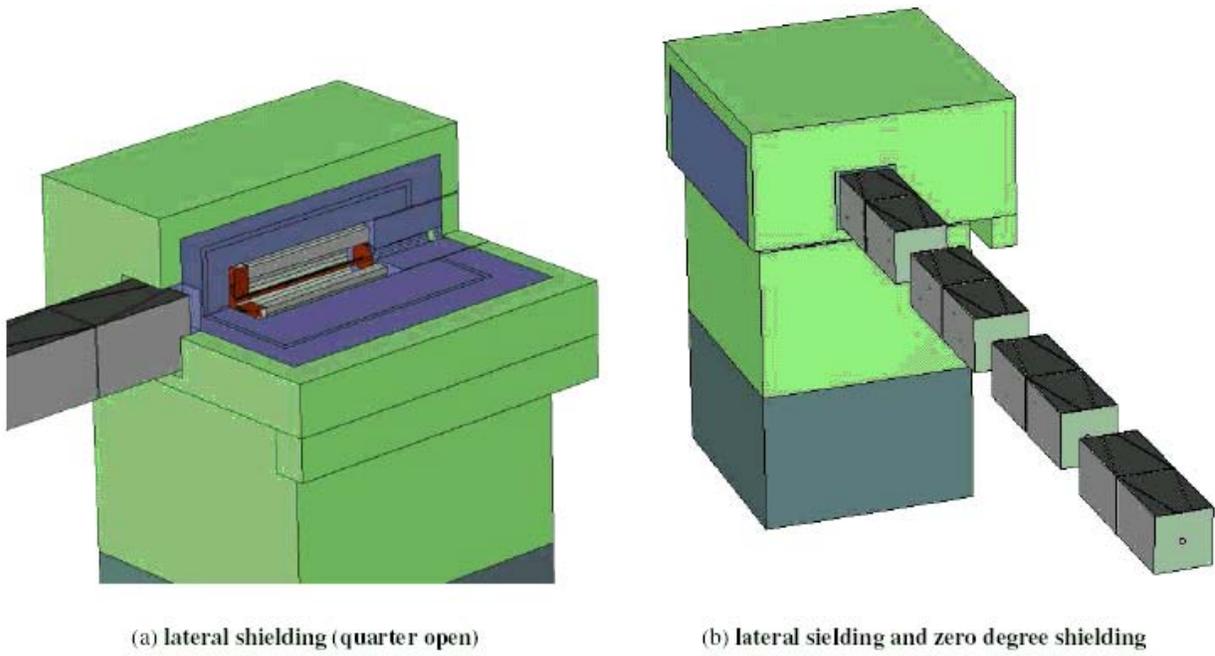


Figure 8 a) Lateral shielding (green is marble, blue is polyethylene) around tdkik (red) and b) zero degree shielding (lead blocks in grey).