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ARTICLE

Radiation protection aspects in the vicinity of TW class laser systems

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Modern laser systems are able to generate ionizing radiation of significantly high energies by focusing ultra-short intense pulses onto targets. This study is focused on evaluating possible radiological hazards resulting from the fs high repetition rate laser, operating in a high intensity regime. Characteristics of radiation field generated within a typical experiment of electron acceleration are explored both theoretically and experimentally. The electron bunches with the charge of ~ pC, the pulse duration of ~fs, and 100 MeV energy in a single shot regime were chosen as a benchmark. First, the shielding capabilities of the civil structure surrounding the interaction chamber were examined. Second, responses of typical personal dosimeters (film, TLD, and electronic personal dosimeter), designed for usage in continuous fields, were studied in a pulsed radiation field. Measurements were performed at a Ti:Sapphire 25 TW laser system recently installed at PALS Research Centre in Prague. In accordance with the ALARA principle, the adequacy of an existing bulk shielding for the model electron acceleration experiment was verified and working regime was recommended.

Keywords: pulsed field; fs laser; electron acceleration; shielding; Monte Carlo simulation; film dosimeters; TLD

1. Introduction

Modern laser systems are able to generate ionizing radiation of significantly high energies by focusing ultra-short, intense pulses onto targets. Therefore, radiation safety of both public and personnel has to be ensured at laser facilities.

This paper is focused on evaluating possible radiological hazards resulting from the fs high repetition rate laser of TW class, operating in a high intensity regime. First of all, the shielding capabilities of a civil structure surrounding the interaction chamber need to be examined and shielding suitability confirmed. Second, responses of the typical personal dosimeters in a pulsed radiation field are studied. Although nobody is present in the experimental hall during the laser operation, it is important to confirm the reliability of personal dosimeters, since they have been originally designed for measurements in continuous radiation fields.

Recently, a Ti:Sapphire laser system has been installed at PALS Research Centre in Prague. A first attempt to assess characteristics of radiation field generated within a typical experiment of an electron acceleration has been made. All radioprotection considerations were done for a maximal expected operational scenario, i.e. 100 MeV electron beam, 6.10^6 electrons per shot [1], 240 shots per day (4 series of shots in a repetition rate of 1 Hz).

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2. Methods

2.1. Calculations

Monte Carlo transport code FLUKA [2] and the FLAIR interface [3] were used to create a model of the Ti:Sapphire experimental setup, see **Figure 1.** Two simplified interaction chambers were modeled as spherical steel shells of 80 cm outer diameter and a wall 1 cm thick. The laser target was located in the centre of the left (western) chamber. The beam was impinging the eastern concrete wall, behind which a non-occupied machinery room and a lawn with no public access are located. The north wall, parallel to the beam, is a thick structural concrete wall with supporting columns. The south wall is made of 15 cm brickwork, with 3 cm thick wooden doors, connecting the experimental and laser hall. A technical low occupancy room is located behind the west wall.

Calculations were performed for an electron beam of 100 MeV mean energy and 10° divergence, containing 6.10^6 primary electrons per shot. The defaults supplied by FLUKA were implemented for material compositions and densities.

The ambient dose equivalent was calculated, as well as electron and photon fluences. In order to judge possible radiological hazards, dose rate maps were created. For the purpose of this calculation, the hall was covered by a three-dimensional mesh – blocks of a few cm in size.

Preliminary activation study for a steel slab 1 cm thick, irradiated for 100 s by a 100 MeV electron beam from the 39 cm distance was run. Under these conditions, the induced radioactivity within the slab was calculated 10 s, 60 s, 10 min and 1 h after the end of irradiation.

2.2. Measurement

The electron acceleration experiment was carried out at the CPA [4] 25 TW Ti:Sapphire laser system at PALS. The laser, operating at the central wavelength of 810 nm, is delivering the laser pulses with the energy of 1 J and the duration of 40 fs. During the experiment, 180 electron beams were produced from a gaseous nitrogen target of 10^{18} cm^{-3} density and backing pressure of 1.3 MPa.

Prior to the experiment, a long term measurement of background was performed in the experimental hall using an electronic personal dosimeter (EPD) from November 2011 till April 2012.

One active dosimeter, EPD, and two types of passive dosimeters, thermoluminescent chips (TLD) and films were used for dose measurements. 19 measurement locations were identified, both inside and outside the interaction chamber, see Figure 1. At 10 locations, film and TLD dosimeters were positioned in pairs. Either film or TLD dosimeters were placed in the remaining 9 locations. All dosimeters were located on the target/beam level, i.e. 140 cm above floor, except for 3 on the top and bottom of the chambers.

2.2.1 Electronic personal dosimeter

An electronic personal dosimeter Mk2 EPD 2.3 (Thermo Scientific) was positioned 1.5 m from the target, i.e. outside the interaction chamber, near position 17, see Figure 1. The dosimeter contains three silicon diode detectors that measure soft gamma, hard gamma, and beta radiation. Outputs are processed and dose equivalents Hp(10), Hp(0.07) and dose rates are given with typical uncertainty of 30%. Sensitivity of the dosimeter is declared to be for photons in the energy range of 15keV to 10MeV and to betas of the mean energy between 250keV and 1.5MeV.

2.2.2 Films

Foma Personal Monitoring Films were used in the film holders, equipped with copper, lead, and plastic filters of different thickness. The films are sensitive to β, X, and γ radiations. Dose equivalent is measured in the range of 0.05 mSv-2 Sv, with typical uncertainty of 25%. Calibrated energy range is from 10 keV to 15 MeV for photons, 0.5 MeV to 15 MeV for betas.

2.2.3 TLD

Five pieces of TLD-700H (^{7}LiF:Mg, Cu, P) chips were located at each TLD measurement position and their responses were averaged to reduce statistical uncertainty. TL responses were read-out at heating ramp 10 °C/s from 160 °C to 300 °C in an N_2 atmosphere using a PC-aided Harshaw Model 3500 reader.

3. Results

3.1. Calculations

Neutron, photon, and electron fluencies were calculated. Although some neutrons are produced, neutron fluence is several orders of magnitude lower than electron or photon fluencies. **Figure 2** shows total photon fluence per one shot averaged across the full hall height and **Figure 3** distribution of the dose equivalent on the beam level. As anticipated, majority of particles continue in the beam direction. Naturally, the wooden doors are a weak point, through which the radiation leaks to the laser hall, where the operator works.

Table 1 summarizes the expected dose rate levels for an anticipated maximal regime of 240 shots a day. The dose rates are high inside the interaction chambers, up to tens of mSv per shot in the beam direction. Fortunately, the 1 cm thick steel chamber wall represents a good shielding for both electrons and secondary photons. Therefore, the doses outside the chambers are several orders of magnitude lower. It appears it is safe to work in the laser hall during the beam operation, as the maximum expected dose, received in the direct connection with the laser operation, is about 0.5 mSv per year.

Radiation exposure can be further reduced by minimizing the time spent in the critical area, i.e. behind the wooden door, additional local shielding is not requested.

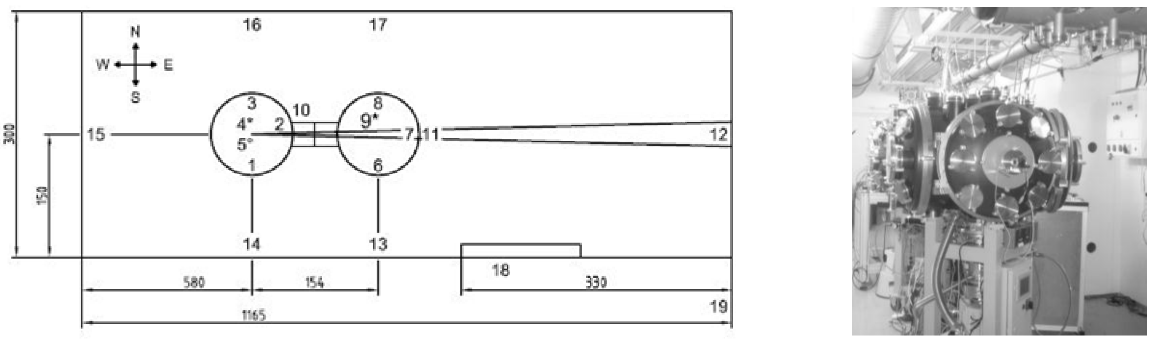

Figure 1. (a) Sketch of experimental arrangement of Ti:Sapphire laser system - schematic view of measurement locations. All the locations are vertically on the beam level, with exception of 4 and 9 that are inside the interaction chamber, 39 cm above the beam level and 5 that is on the bottom of the interaction chamber, 39 cm below the beam level. (b) Photo of the interaction chamber.

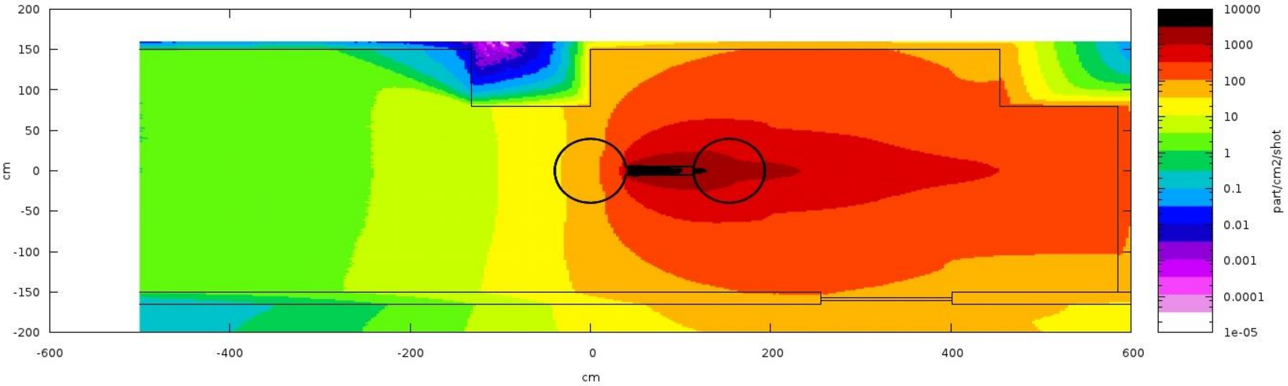

Figure 2. Calculated total photon fluence (particle/cm^2) per one shot of 100 MeV electron beam of 6.24.10^6 primaries, averaged across the full hall height.

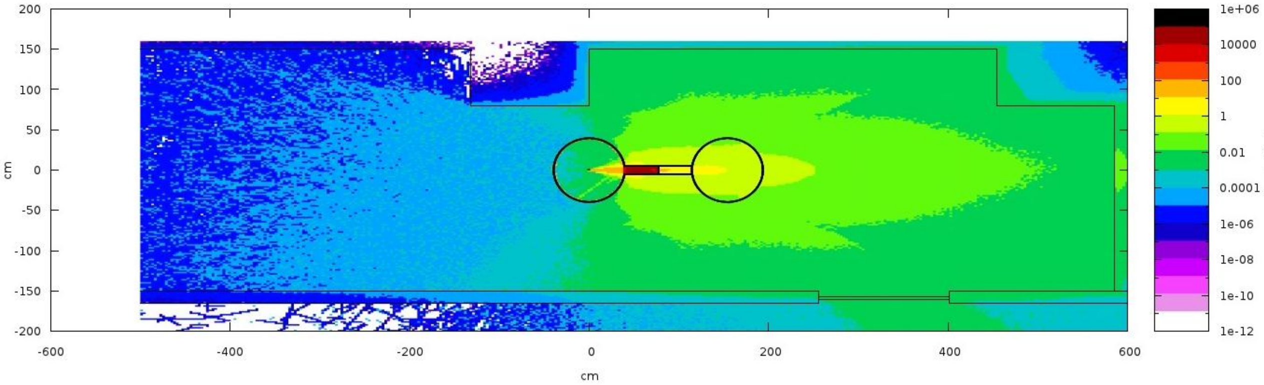

Figure 3. Distribution of calculated dose equivalent (μSv) per one shot of 100 MeV electron beam of 6.24.10^6 primaries, on the beam level only.

A great variety of radionuclides are induced within the steel slab. Nevertheless, the total activity of the slab is only several mBq/cm^3, see **Table 2**, which also lists radionuclides contributing highest to the total. Activation of the air behind the steel slab is below 10^{-8} Bq/cm^3, the largest contributors being ^{15}O and ^{13}N.

3.2. Measurements

3.2.1 Electronic personal dosimeter

The long term EPD measurement in the experimental hall gave an average daily background of 2.1 μSv, which is in agreement with the average equal to 2.5 μSv/day measured in Prague during the first quarter 2012 [5].

Borne et al [6] found EPDs response to laser produced radiation unsatisfactory: While films and TLDs responses were comparable (several mSv), responses of all EPDs used were virtually zero (<1 μSv).

Despite the negative expectations, the EPD responded well in our experimental setup, even though the pulses of primary radiations were order of magnitude shorter than in Borne's experiment. As Borne's interaction chamber is similar (1 cm thick steel, 1 m in diameter), the crucial difference between the two setups is the EPDs position. Borne's group placed EPDs directly on the outside of interaction chamber, while ours was 1.5 m from the target (i.e. ~1 m from the outside chamber wall). Apparently, pulse length widening has been sufficient for the EPD to detect dose rate adequately.

The majority of beams were generated within 2 hours on the first day. During that time, dose equivalent rate Hp(10) reached its maximum 0.32 μSv/h. This value (after background subtraction) equals twice the long term background average and is in good agreement with TLD and FLUKA results, see **Table 3**.

Beams generated on the two following days had an insignificant effect on the EPD response. Beams were probably too far apart to influence the EPDs dose rate response which is averaged over a certain period of time.

Table 1. Typical calculated expected doses at different areas (interaction chamber=IC, experimental hall=EC). The approximate values of daily and annual dose are given for the expected regime of 240 shots a day and 200 shooting days a year.

Location	Daily dose [μSv]	Annual dose [mSv]
Inside IC	240-2.4.10^6	48-480000
Vicinity of the IC	2.4-24	0.5-4.8
EH, half with the beam	0.24-2.4	0.048-0.480
EH, opposite direction to the beam	<0.24	<0.048
Laser control room, behind the door	0.24 -2.4	0.048-0.480
Laser control room, more exposed part	<0.24	<0.048

3.2.2 Film measurement

Responses of the film dosimeters are summarized in **Table 4**. Dosimeters for the long term measurement were exposed continuously for 3 months, starting a week before the main experiment was run. For position 2 (inside chamber, close to the beam) an emergency film present within the holder was developed in addition to the normal film. Responses of both films were found to be consistent with a balanced contribution of photons and electrons to the dose.

Despite expectations, the dosimeter at position 3 (inside chamber, perpendicular to the beam direction) showed the second highest dose, which comes almost entirely from electrons. It is likely that plasma generating the beam is the main contributor to the dose. It was not possible to fully evaluate the response at position 5 due to a technical problem of the film foil. Response of the film at position 10 demonstrated directionally dependent exposure by X rays. This corresponds well to its location outside the chamber, near the connecting tube.

3.2.3 TLD measurement

In general, responses of TLDs and films correspond excellently, see Table 4, with the exception of position 4 (top of the inside of the interaction chamber). Film at position 4 was only partially exposed correctly; it fell down during the experiment and was therefore shielded by a dural board for an unknown period of time.

4. Conclusion

Both calculation and measurement suggest that operating Ti:Sapphire laser in a regime producing 100 MeV electrons (6.10^6 electrons/shot, 240 shots/day) does not represent any radiation health risk neither for public, nor for personnel; however, access prohibition to the experimental hall during laser operation is vital. Although the expected annual dose in the most exposed part of the laser control room is only 0.5 mSv, the occupancy should be kept to the necessary minimum.

It is recommended to wait 10-15 min before working with the chamber and its equipment after the shot sequence. However, more detailed activation analysis needs to be performed.

No additional shielding is required for the given setup and working regime. Should the arrangement change, re-assessment of the topic would be necessary.

Response of EPD was found to be promising for use as a supplement to passive dosimeters. Nevertheless, further studies need to be performed to confirm adequacy and relevance of its response in pulsed fields.

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Table 2. Induced activity (mBq/cm^3) of the 1 cm thick steel slab 10s, 60s, 10 min and 60 min after the end of irradiation. Activities of the most contributing radionuclides are given.

	half-life (min)	Induced activity (mBq/cm^3) 10s	60s	10 min	60 min
Total		8.8	7.6	2.8	0.2
^{53m}Fe	2.58	5.0	4.0	0.4	0.00
^{53}Fe	8.51	2.3	2.4	1.8	0.03
^{52}V	3.743	0.4	0.4	0.1	0.00

Table 3. Comparison of responses of TLD, EPD and FLUKA at the same location for 90 shots. Responses are corrected for background. Note: * average background in Prague [4]

	Background [µSv/h]	Response [µSv/h]	Ratio: Dose rate/background
TLD	0.12	0.21	1.8
EPD	0.09	0.23	2.6
FLUKA	0.106*	0.15	1.4

Table 4. Calculated and measured values of the dose equivalent, corrected for background. See Figure 1 for ID location. Note: # emergency film, &partial dose (the dosemeter fell off),

ID	FLUKA [mSv]	TLD [mSv]	Film [mSv] Photons	electron	sum
Inside of the interaction chamber					
1	7.21	9.2	0.19	9.14	9.33
2	42.4	33.9	17.7	16.3	34
	-	-	16.3#	16.8#	33.1#
3	10.4	21.5	0.12	24.1	24.22
4	2.33	10.7	0.18&	5.6&	5.78&
5	5.64	0.8	contribution of electrons		
Inside eastern chamber					
6	0.01	0.00	-	-	-
7	0.08	0.09	0.13	0.00	0.13
8	0.01	0.00	0.00	0.00	0.00
9	0.01	-	0.00	0.00	0.00
Outside chambers, inside experimentall hall					
10	0.20	-	1.67	0.00	1.67
11	0.10	-	0.05	0.00	0.05
12	0.00	0.02	0.03	0.00	0.03
13	0.00	0.03	0.02	0.00	0.02
14	0.00	0.01	-	-	-
15	0.00	0.01	0.00	0.00	0.00
16	0.00	0.02	-	-	-
17	0.00	0.01	-	-	-
Inside laser control room					
18	0.00	-	0.00	0.00	0.00
19	0.00	-	-	-	-
Long term measurement (3 months)					
12	-	-	0.08	0.00	0.08
16	-	-	0.03	0.00	0.03
19	-	-	0.00	0.00	0.00

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