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SHIELDING CALCULATIONS FOR THE HARD X-RAY GENERATED BY LCLS MEC LASER SYSTEM

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LCLS Matter in Extreme Conditions (MEC) Instrument is an X-ray instrument that will be able to create and diagnose High Energy Density (HED) matter. The MEC laser system can generate hard X-ray due to the interaction of the laser and the plasma. This paper summarizes results of the shielding calculations performed to evaluate the radiation hazards induced by this hard X-ray source with Monte Carlo code FLUKA. The dose rates and photon spectra due to this X-ray source are calculated at different locations with different shielding. The influence of the electron temperature on the source terms and the shielding effectiveness was also investigated.

KEY WORDS: *LCLS, laser induced X-ray, shielding*

INTRODUCTION

The Linac Coherent Light Source (LCLS), the world's first X-ray free electron laser, is being built at SLAC National Accelerator Laboratory. This facility utilizes the SLAC 2-Mile Linear Accelerator (linac) and will have two experiment halls, the Near Experimental Hall (NEH) and the Far Experimental Hall (FEH) [1].

LCLS Matter in Extreme Conditions (MEC) instrument is an X-ray instrument that will be able to create High Energy Density (HED) matter and measure its physical properties [2]. It will utilize either the LCLS beam and/or one or more optical lasers focused onto the target to create matter in extreme conditions. The MEC instrument will include a suite of optical and x-ray diagnostics to fully characterize those states. The main components in a typical MEC experiment include the drive beams to excite the matter and a suite of diagnostics arraigned around the sample to diagnose the sample. The sample and the associated diagnostics are located within a large target chamber that can accommodate both the optics for the optical drive beams along with the diagnostic suite.

The Matter in Extreme Conditions instrument will combine high energy and/or high peak power laser systems with the LCLS x-ray beam to create and probe states of matter inaccessible under static conditions. The LCLS beam provides a unique probe to study these states of matter via spectroscopy, Thomson scattering, imaging and diffraction. In addition it can be used to create these states of matter in ways not possible with optical lasers.

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Fig. 1 shows a drawing of the target chamber and laser systems within the MEC instrument hutch. Also shown are the main shielding items including the hutch wall and the roll-up door, which is for the entry of big size instruments. There are two optical laser systems in the MEC instrument hutch: 1) a 150 mJ, 40 fs short-pulse laser and 2) a high-energy long-pulse system producing >50 J at a green wavelength with pulse width varying between 200 ps to 200 ns [3].

It is known that hard X-rays can be produced by the hot electrons that are present in the plasma as a result of laser plasma interactions[4~8]. When the hot electrons interact with ions, they produce X-ray bremsstrahlung radiation, which becomes a hard X-ray source. Since the LCLS beam line hutch shielding for the FEH hutch was originally designed mainly considering the protection against spontaneous radiation and free electron laser beam, it is necessary to evaluate the shielding effects for this hard X-ray source.

This paper summarizes results of the shielding calculations performed to evaluate the radiation hazards induced by the hard X-ray source generated by MEC laser system. The dose rates due to this X-ray source were calculated at different locations with different shielding configurations for the MEC instrument hutch. Here the radiation hazard issue is only addressed for the short pulse laser since the short pulse laser can produce a stronger X-ray source due to the higher laser intensity and higher frequency.

X-RAY SOURCE TERM

When a high power laser pulse strikes a solid target, a characteristic sequence of energy conversion process leads to a hot, dense plasma consisting of matter in extreme state of high energy concentration[4]. Then hot electrons are produced as a result of the generation of electron plasma waves through a resonant interaction between the laser and the plasma. The interaction can result in a scattered light photon and a high frequency electron plasma wave, which is called Stimulated Raman Scattering (SRS). It can also result in two plasma waves (Two Plasmon Decay Instability). Both the processes extract energy from the incident laser beam and SRS is the most dominant process. SRS becomes unstable when the interaction between the incident and scattered photons or plasma waves becomes part of a feedback loop that enhances the plasma wave. Damping of the plasma wave can result in electrons that have been accelerated to the phase velocity of the wave, with kinetic energies of 10’s to 100’s of keV.

These hot electrons have an energy distribution (Maxwellian shape) that is characterized by a temperature, T_h. This electron temperature is typically in the range of 20 -100 keV and dependent on the laser wavelength, peak laser intensity (in unit of W/cm^2) and the target material. The phase velocity of the plasma wave is a strong function of the plasma electron density as is the observed T_h. The quantity of hot electrons is characterized by a fraction f_{hot} of the energy in the hot electrons relative to the incident laser energy. The hot electrons produce X-ray bremsstrahlung radiation when they interact with ions of the target, and the process is most efficient when high-Z ions are present. The X-ray photons produced will have energies of 10's to 100's of keV. The photon yield is determined by the energy of the laser pulse incident on the target, the fraction of energy that is converted into kinetic energy of fast electrons, the energy spectrum of the electrons and the efficiency of conversion from electron kinetic energy to X-rays.

Studies have shown that this X-ray bremsstrahlung radiation spectrum can be expected to be [5, 6]:

$$N_p(E_p) = C\frac{1}{E_p}\exp(-\frac{E_p}{T_h})sr^{-1} \quad (1)$$

where E_p is the photon energy in keV, T_h the electron temperature in keV and C a constant. C should satisfy that the integration of the photon energy equals to the product of the laser pulse energy and ε, the laser to X-ray conversion efficiency. Therefore C is dependent on the electron temperature, the laser pulse energy and the laser to X-ray conversion efficiency and can be computed as long as these parameters are known.

A conservative estimation of the laser energy to X-ray conversion efficiency of 1.3×10^{-4} and a typical electron temperature of 40 keV for Ag[5] were used in this study. Based on the energy of MEC short pulse laser (150 mJ) as well as the assumption for the laser energy to X-ray conversion efficiency and the electron temperature, the value of constant C can be computed as 2.5×10^8.

As far as the photon spectrum and the shielding effects are concerned, the electron temperature is a very important parameter. Therefore the same calculation for the case at a higher electron temperature of 100 keV was also carried out to investigate the influence of this parameter. Under this condition, based on the assumption that the laser energy to X-ray conversion efficiency is the same (1.3×10^{-4}), the value of constant C can be computed as 1.0×10^8. However, it should be pointed out that the laser to X-ray conversion efficiency in this case may be smaller compared to a lower electron temperature.

SHIELDING CALCULATION

The calculation is performed using the FLUKA code [9,10], a multi-particle, multi-purpose Monte Carlo code for radiation transport and interaction.

The main shielding items for the hard X-ray generated by MEC laser system in the MEC instrument hutch include the Al-wall target chamber, the lead hutch wall, and the roll-up stainless steel (SS) door as shown in Fig. 1. The shielding effects of these shielding items for this hard X-ray source were evaluated.

The ambient dose equivalents H* were calculated. The photon spectra were also recorded and compared outside different shielding in order to obtain a better understanding of the shielding effect.

X-ray source in simulation

A FLUKA source routine was written in order to sample primary photons from the spectrum described in Equation (1) with T_h = 40 keV. The sampling was verified by comparison between the spectrum recorded with FLUKA and the one from the equation, as shown in Fig. 2. In the simulation it was assumed that the source is a point source and the source photons are emit isotropically.

In order to obtain the photon intensity, a Fortran routine was written to integrate the spectrum described by Equation (1). The minimum photon energy was set to be 1 keV since it is the transport threshold of FLUKA code, and the maximum photon energy was set to be 1 MeV. It is found that the photon number in one laser shot is 9.85×10^9at the electron temperature of 40 keV and 4.12×10^9 at the electron temperature of 100 keV, which is used for FLUKA dose result normalization.

Geometry

A generic geometry was used in this simulation with FLUKA as shown in Fig. 3.

Al chamber wall was defined as a spherical shell with thickness of 1 inch. The point source was located at the center of the spherical shell. The distance from the source to the inner surface of the Al chamber wall is 1 m. The lead wall or SS door was defined as another spherical shell at 5m away from the source. The thickness of the wall and the door is 1/16 inch and 1.2141mm.

Transport setting and scoring

The transport cut-off for the photons and electrons were set to be 1 keV, which is the FLUKA transport threshold. The ambient dose equivalents were computed by folding the particle fluence with the ambient dose equivalents conversion coefficients.

RESULTS

Ambient dose equivalents

The ambient dose equivalents from one laser shot were calculated by multiplying the ambient dose equivalents contributed by one primary photon with the total photon number in one shot. The ambient dose equivalent rates could be derived by taking the laser frequency into account. Though MEC PRD[5] states that higher frequency is possible, the average frequency of 1 Hz for the most likely short-pulse laser mode of operation was used.

The results without any shielding and those outside the Al-wall target chamber, the lead wall, and the roll-up SS door at different distances are listed in Table I and Table II for electron temperature of 40 keV and 100 keV, respectively. The dose for locations D0 to D5 are calculation results from FLUKA. Dose for D6 is rescaled from the one for D5 with the nearest distance from the center of the target chamber to the roll-up door in MEC instrument hutch.

The ambient dose equivalent rate directly from this hard X-ray source at the electron temperature of 100 keV is 33% lower than the one at the electron temperature of 40 keV. However, outside the shielding the dose rate becomes higher with 100 keV electron temperatures.

At a laser pulse of 1-Hz, the ambient dose equivalent rate outside the Al target chamber is 0.42 mrem/h at the electron temperature of 40 keV and almost twice higher at the electron temperature of 100 keV. The maximum ambient dose equivalent rate outside the MEC instrument hutch occurs at the location outside the roll-up SS door in both cases with different electron temperature. The ambient dose equivalent rate is 6.0×10^{-3} mrem/h at the electron temperature of 40 keV, which is almost ten times lower than the shielding design limit of 0.05 mrem/h. However, when the electron temperature is 100 keV, the ambient dose equivalent rate outside the roll-up door is 1.6×10^{-2} mrem/h, approaching this limit.

Photon spectra

Fig. 4 and Fig. 5 show the photon spectra inside the chamber and outside different shielding calculated with FLUKA at the electron temperature of 40 keV and 100 keV, respectilvely. The spectra were normalized and correponds to the contribution by one primary photon.

It could be found that the effects on the photon spectrum by the shielding show the similar trend in both cases with different electron temperature. The Al chamber is only effetive for the attenuation of the photons which energy are below 50 keV. The Pb wall is quite efficient for the shielding against photons up to 300 keV. And the K edge of lead at 88 keV could be observed clearly in the spectrum outside the lead wall.

Comparatively the steel door only provides a little bit shielding for the photons below 70 keV for the already aluminum-harden spectrum. At the same time the distance from the Al chamber to the wall or door gives a reduction factor of 0.04 in both cases with different electron temperature, which is consistent with the inverse square law.

Shielding effects

The attenuation factors of the Al chamber wall, the lead wall and the roll-up SS door were calculated respectively for the two electron temperature cases and comapred in Table III.

It shows that every shielding item has a larger attenuation factor at the electron temperature of 100 keV due to the harder spectrum compared to the one at the electron temperature of 40 keV. The attenuation factor was increased by a factor of 1.4 (for 1.2141mm Steel) to a factor of 5.5 (for 1/16 inch lead).

SUMMARY

Detailed calculations of the prompt dose due to hard X-ray generated by the plasma induced by MEC short pulse laser (150 mJ, 40 fs, 1-Hz) system were performed using the FLUKA code for the radiation safety of the MEC instrument hutch at LCLS. A conservative estimation of the laser to X-ray conversion efficiency of 1.3×10^{-4} and a typical electron temperature of 40 keV was used in the calculation. The influence of the electron temperature on the source terms and the shielding effectivess was also investigated by an additional calculation with an electron temperature of 100 keV. The results are:

1) The dose rate is high (0.42 mrem/h at the electron temperature of 40 keV and 0.80 mrem/h at the electron temperature of 100 keV right outside the Al target chamber) inside the MEC instrument hutch.

2) As far as the MEC short pulse laser and an electron temperate of 40 keV are concerned, the ambient dose equivalent rate outside the hutch generated by the hard X-ray source is 6.0E-3 mrem/h, much lower than shielding design limit of 0.05 mrem/h. It should be noted that the dose rates calculated in this work is for a laser pulse of 1-Hz operation. The dose rates at higher laser frequencies could be scaled in proportion and be higher. For example, at 10-Hz, the dose rate outside the hutch is 0.06 mrem/h, exceeding the design limit.
3) A higher electron temperature of 100 keV reduces the source term (dose rate inside the chamber without any shielding) by 33%, but it also reduces the shielding effectiveness against the hard X-ray source by a factor of 1.4 to a factor of 5.5 due to the harder photon spectra.

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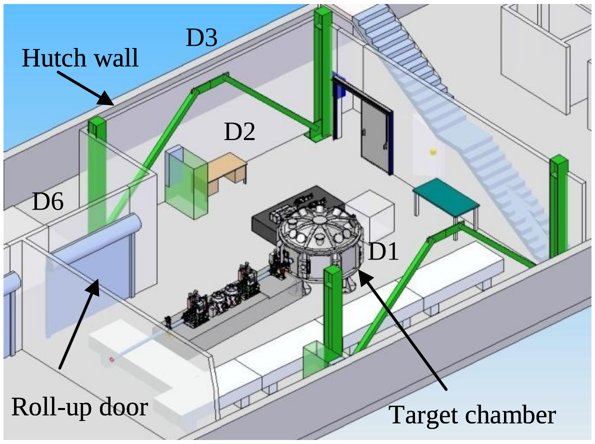

Fig.1 Layout of the MEC instrument hutch.

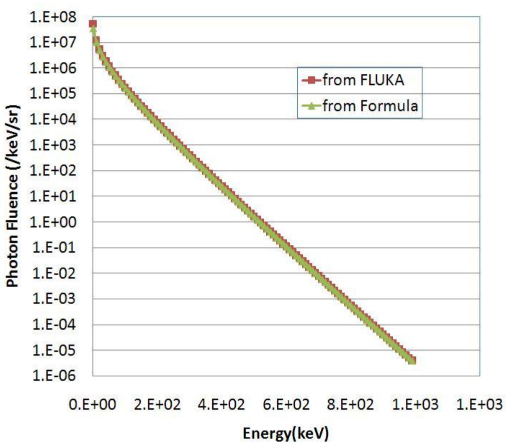

Fig.2 Comparison of the X-ray source spectrum between the one from FLUKA and from Formula (1) with 40 keV electron temperature.

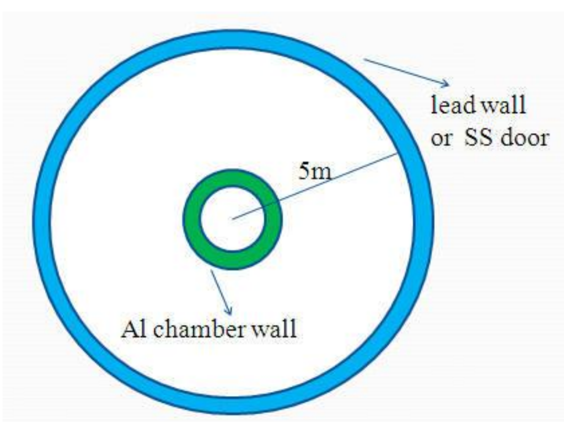

Fig.3 Geometry used in simulation with FLUKA

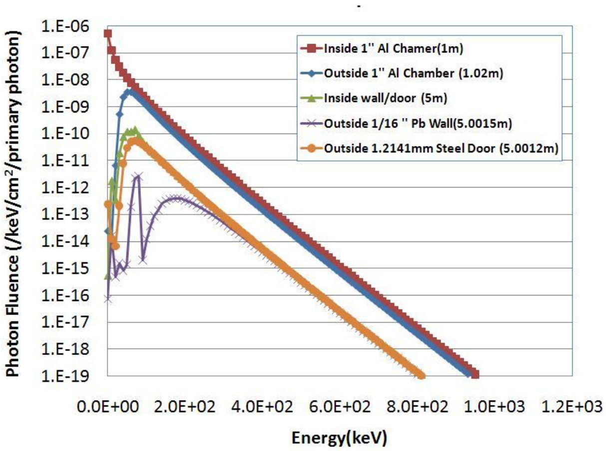

Fig. 4. Photon spectra inside the chamber and outside different shielding at the electron temperature of 40 keV

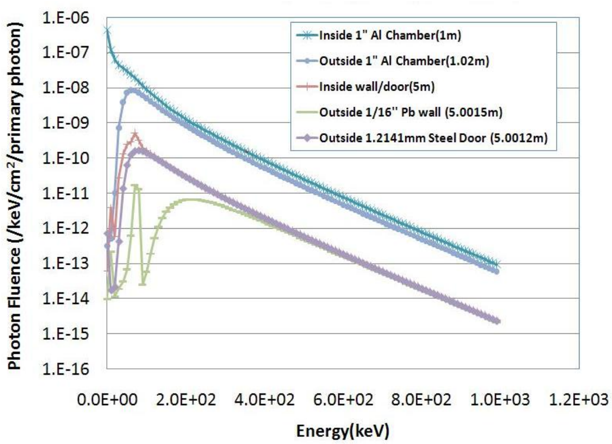

Fig. 5. Photon spectra inside the chamber and outside different shielding at the electron temperature of 100 keV

Table I. Ambient dose equivalent rate at different positions at 1-Hz (T_h=40 keV, ε =1.3x10^{-4})

Location	Description	Distance	Ambient dose equivalent rate	
		m	mrem/shot	mrem/h
D0	without any shielding	1.00	1.8E-03	6.5E+00
D1	outside the chamber (1 inch Al)	1.02	1.2E-04	4.2E-01
D2	inside the wall/door	5.00	4.4E-06	1.6E-02
D3	outside the wall(1/16 inch Pb)	5.0015	8.1E-08	2.9E-04
D5	outside the door (1.2141mm Steel)	5.0012	2.1E-06	7.7E-03
D6	outside the door (1.2141 mm Steel)	5.6512	1.7E-06	6.0E-03

Table II. Ambient dose equivalent rate at different positions at 1-Hz (T_h=100 keV, ε =1.3x10^{-4})

Location	Description	Distance	Ambient dose equivalent rate	
		m	mrem/shot	mrem/h
D0	without any shielding	1.00	1.2E-03	4.3E+00
D1	outside the chamber (1 inch Al)	1.02	2.2E-04	8.0E-01
D2	inside the wall/door	5.00	8.3E-06	3.0E-02
D3	outside the wall(1/16 inch Pb)	5.0015	9.5E-07	3.4E-03
D5	outside the door (1.2141mm Steel)	5.0012	5.7E-06	2.0E-02
D6	outside the door (1.2141 mm Steel)	5.6512	4.4E-06	1.6E-02

Table III. Attenuation factor of different shielding at two conditions with different electron temperature

Shielding items	Attenuation factor	
	T_h=40 keV	T_h=100 keV
1 inch Al chamber wall	0.07	0.18
1/16 inch lead wall	0.02	0.11
1.2141 mm Steel	0.49	0.68