Considerations on the composition and spectra of the secondary radiation fields inside the E1 experimental area at ELI-NP

Maria – Ana Popovici¹, Radu A. Vasilache²

¹Bucharest Polytechnical University, Faculty of Applied Sciences, Bucharest, Romania
²Canberra Packard Ltd., Bucharest, Romania

Abstract. At the new ultrahigh power laser facility ELI NP, experiments on the interaction of high power lasers and matter will be conducted. These experiments are expected to produce beams of highly energetic particles resulting in secondary radiation fields which will be highly complex and rather difficult to measure given their specifics (extremely short bursts, with time widths in the range of nanoseconds). The ELIFLUKA project was started to assess the doses in the areas surrounding the experimental halls, to evaluate the efficiency of the existing shielding solutions, to propose, if necessary, their optimization, and give optimal ways to monitor the radiation fields that might affect the facility personnel. The present paper is focused on the results concerning the composition and the spectra of the secondary radiation fields inside the E1 experimental hall. A complex FLUKA geometry of the E1 area was built according to the real design of the experimental hall. With FLUKA we calculated the particle fluences, the spatial distribution and spectra of each component of the radiation field, corresponding to two limit source terms, characterised by a thermal energy distribution with 40 MeV average and 250 MeV cut-off, and a second one with a flat energy distribution with 500 MeV average and 50 MeV FWHM. The FLUKA code was used to calculate all particle fluence spatial distribution inside the experimental hall, as well as the fluences and spectra for the main components of secondary radiation fields. These results can be used to design various experimental setups at E1 in such a way that the instruments would be positioned without risking significant activation and/or radiation damage and they provide a source term for the shielding calculations using the classical methods, as usually requested by the regulatory authorities.

1. Introduction
The new ultrahigh power laser facility ELI-NP from Magurele, Romania, will be the host of a wide range of experiments experiments regarding the interaction of 10 PW class power lasers and matter [1]. The interaction between the high power laser and the targets will produce beams of highly energetic particles and, consequently, secondary radiation fields of high complexity. Due to the specifics of these radiation fields (extremely short bursts, with time widths in the range of nanoseconds), it will be rather difficult to measure the fluences and the doses both for radiological protection purposes and to assess the best experimental set-up inside the bunker. For this reason we started the ELIFLUKA project, in which we set out to assess the doses in the areas surrounding the experimental halls, to evaluate the
efficiency of the existing shielding solutions, to propose, if necessary, their optimization, and give optimal ways to monitor the radiation fields that might affect the facility personnel.

The present paper is focused on the results concerning the composition and the spectra of the secondary radiation fields inside the E1 experimental hall. The FLUKA geometry of the E1 area was built according to the real design of the experimental hall, as extracted from the corresponding Catia file and then we calculated the particle fluences, the spatial distribution and spectra of each component of the radiation field, corresponding to two limit proton source terms, in the low and high energy range, as described in the following section. Both beams have a large full divergence angle, of 45° and 40° respectively. The first one, in the low energy range, will be achieved soon after the beginning of the experiments whilst the second one, in the high energy range, is expected to be achieved at a later stage. The FLUKA code [2,3] was used to calculate all particle fluence spatial distribution inside the experimental hall, as well as the fluences and spectra for the main components of secondary radiation fields. These results can be used to design various experimental setups at E1 in such a way that the instruments would be positioned without risking significant activation and/or radiation damage. Also, they provide a source term for the shielding calculations using classical methods, as usually requested by the regulatory authorities.

2. Method
A complex FLUKA geometry of the E1 area was built according to the real design of the experimental hall, as extracted from the corresponding Catia file. The choice of the source terms was done taking into account proposed experiments as presented in TDR E1 [4]. As most of the experiments planned at E1 involve the use of proton beams, we have selected two limit source terms, in the low and high energy regimes. They are defined as follows:

- Low energy proton source: thermal energy distribution of 40 MeV average value, with a 250 MeV cutoff; beam divergence half angle is 25 degrees; 6x10^12 protons per laser pulse at a repetition rate of 1 pulse per minute.
- High energy proton source: uniform energy distribution of 500 MeV average value, with a 50 MeV FWHM; beam divergence half angle is 20 degrees; 1.4x10^12 protons per laser pulse at a repetition rate of 1 pulse per minute.

For each of these sources, the values of all particle fluence, as well as field components fluencies (photons, neutrons, muons, electrons and positrons, primary and secondary protons) have been computed throughout the E1 experimental area. Figures 1 a and b show just a sample of these results: the all particle fluence maps for a horizontal section at the beam height level (1.5 m above floor) summed over a 10 cm height layer centred on the source axis plane. Based on all of these values, we have defines test areas (“detectors”) necessary to calculate the energy spectra for the field components. The position of the test areas has been selected taking into account the possible positioning of the experimental instrumentation. The information about the spectra and fluence of each field component in the test areas can be used for a better planning of each experiment.
As the radiation field in the experimental area is strongly influenced by the beamdump, a point of interest for the FLUKA calculations are the upstream and downstream components of the field. The other very important influence on the radiation field (especially on the upstream component) is the interaction chamber itself, which has 10 cm aluminium alloy walls. This turns the interaction chamber itself into a source of secondary radiation.

![Figure 2. Geometry of the simulated E1 area (detail). Detectors: TEST1 to TEST3 between interaction chamber and beamdump, BDW1 and 2 at the beamdump entrance (west), BDE1 and 2 at the beamdump exit (east, in front of a channel and in between channels, respectively) and BDS at the right lateral side of the beamdump (south)](image)

Taking into account all of the above considerations, the test areas were selected as follows:

- TEST1, 2 and 3 are planes situated at equal distances between the interaction chamber exit windows and the beamdump entry surface.
- Because the beamdump is traversed by channels needed for experiments behind the beamdump, we have defined the detectors BDW1 and BDW2 at the entry (“west”) surface, corresponding to the first channel entry and, respectively to the area between the first two consecutive channels. Similarly, we have defined the detectors BDE1 and BDE2 at the exit surface (east)
- The BDS detector in the south part of the beamdump which, is the best protected area in the experimental hall.

3. Results and discussion

According to the output of the FLUKA run for the 40 MeV source, the total number of low energy neutrons generated is one order of magnitude higher than the total number of inelastic and elastic collisions. In turn, the elastic and inelastic interactions are in fairly equal amounts. Most nuclear reactions at this energy are generated by the protons (~87%), the rest belonging to the neutrons. These generate mostly photons (~37% of the total number) and secondary protons (~31% of the total number) with significant components of neutrons (~18%) and alphas (~11%), the rest of the components having a very low contribution. Another important output of the FLUKA run is the energy balance of the interactions per primary proton: almost 97% of the total available energy is spent in direct linear energy transfer, and only about 2% in electromagnetic showers. The rest corresponds to nuclear recoil and heavy fragment production and in low energy neutron production.

Performing a similar analysis on the 500 MeV source, we see again that the low energy neutrons generated are one order of magnitude higher than the total number of inelastic and elastic collisions, which in turn remain fairly equal. However the total number of nuclear reactions generated per beam particle is two orders of magnitude higher than for the low energy source. In this case the number of
nuclear reaction generated by protons and neutron is similar (almost 50% per component). The fluence values recorded at each detector, for each important field component, are shown in tables 1 and 2 for 40 MeV and 500 MeV, respectively. The secondary radiation field generated in nuclear reactions is, in this case, dominated by the neutrons (~30%), protons (~26%) photons (~24%) and alphas (~14%). In what concerns the energy balance of the interactions per primary proton, the most important part is again the direct linear energy transfer (~80%) with a more important electromagnetic shower component (~11%).

Tables 1 and 2 below show the contribution of selected field components to the total fluence, in some of the test areas, for the 40 MeV and 500 MeV source, respectively.

**Table 1.** Contribution of selected field components to the total fluence, in some of the test areas, for the 40 MeV source term.

|        | All particle fluence (#/cm² / pulse) | Photon fluence (#/cm² / pulse) | Neutron fluence (#/cm² / pulse) | Proton (primary & secondary) fluence (#/cm² / pulse) | Electron and positron fluence (#/cm² / pulse) |
|--------|-------------------------------------|--------------------------------|--------------------------------|-----------------------------------------------|---------------------------------------------|
| TEST2  | 2.69E6 ± 0.47%                      | 1.14E6 ± 0.71%                  | 8.43E5 ± 0.78%                 | 6.87E5 ± 0.81%                                | 2.42E4 ± 4.91%                              |
| BDE1   | 1.32E4 ± 6.77%                      | 2.56E3 ± 14.51%                 | 5.22E3 ± 11.75%                | 5.27E3 ± 9.38                                | 1.78E2 ± 44.23%                             |
| BDE2   | 6.99E3 ± 14.17%                     | 3.25E3 ± 18.49%                 | 3.61E3 ± 18.59%                | 0                                             | 0                                           |
| BDS    | 3.90E4 ± 4.55%                      | 1.40E4 ± 7.67%                  | 2.50E4 ± 5.71%                 | 0                                             | 0                                           |

As it can be seen from these tables, the proton fluence (both primary and secondary) are more than two orders of magnitude higher at 500 MeV than at 40 MeV at the TEST2 and BDE1 detectors (taking into account that the values are normalized per pulse, and the number of protons per pulse is 5 times higher for the low energy source in comparison to the high energy source). Furthermore, behind the beamdump, at the BDE2 detector, there is still a nonzero fluence at 500 MeV, which can only be attributed to the secondary protons.

A similar behavior is observed for the electrons and positrons, where the differences at TEST2 and BDE1 are more than an order of magnitude in favor of the 500 MeV beam. At 500 MeV we have electrons and positrons also behind the beamdump (BDE2 and BDS), due to the higher energy of the
electromagnetic showers. For the photons, the difference ranges between one and two orders of magnitude in favor of the 500 MeV beam, due to the photonuclear reactions which are abundant in this energy range. Also noticeable is the presence of photons in all monitored areas. Finally, the differences in neutron fluence are similar to those for the photons, while, as expected, muons appear in noticeable numbers only at the 500 MeV experiment.

Figure 3. Energy fluence spectra of different radiation field components, at some selected test areas, for the 500 MeV source term: a) neutrons exiting the beamdump, for both BDE detectors; b) photons and muons at the exit from the beamdump, for both BDE detectors; c) neutrons incident on the beamdump, at the BDW1 detector, downstream (In-Out) and upstream (Out-In); d) photon and muon component at the BDW detectors, downstream (In-Out) and upstream (Out-In); e) neutrons at TEST 2, upstream and downstream; f) same as e, for photons and muons; g) neutrons incident on the beamdump, for both BDW detectors; h) neutrons, photons and muons exiting the south side of the beamdump (BDS detector).)

The energy fluence spectra for neutrons, muons and photons generated at the 500 MeV experiment can be seen in figure 3 a) to h). Graphs 3a) and b) show that both neutrons and photons pass through and are also generated in the beamdump. For the neutrons, the energy distribution is largely the same for the BDE1 and BDE2, with the exception of the low energy neutrons which are present in higher numbers at the BDE2. The photons have a drastic difference in spectrum between BDE1 (in front of the channel opening) and BDE2 (behind the beamdump). At the BDE1 detector only higher energy photons are detected (above 1 MeV), albeit with rather low fluencies. At BDE2, the photon spectrum covers a wide range, from very low energies (10-3 eV) to high energies (a few hundred MeV), with a maximum
fluence at very low energy (around 0.1 eV). The fluence drops drastically from the low energy to the high energy: the fluence at high energies is eleven orders of magnitude lower than the maximum fluence.

Between the interaction chamber and the beamdump we recorded the fluences both downstream and upstream, in order to have an image of the contribution of the backscatter (figures 3c to 3f). The neutron component, at BDW1 and TEST2 have largely identical spectra up to the higher energy. The differences appear at around 20 MeV when the downstream direction becomes predominant, due to the higher cross section of nuclear reactions that produce more neutrons in the forward direction. A similar behavior can be seen for the photon component at BDW1 and TEST2, where the spectra are similar for the downstream and upstream directions up to an energy of approximately 150 MeV, when the photons going in the downstream direction become predominant. Moreover, the overall neutron energy spectra at BDW1 and BDW2 are identical (figure 3g). The muon component has a behavior similar to the photons and the neutrons, the difference being that the muons in the downstream direction become predominant at around 30 MeV. The higher scatter in the values for muon fluence at the BDW1 detector reflects a poor statistics due to the smaller area of the detector.

At the BDS detector, neutrons represent the most important component of the radiation field. Their energy distribution covers the range from 10^-4 eV to 200 MeV and the maximum fluence, which appears at thermal energy (around 0.1 eV), is 10 orders of magnitude higher than the fluence at the maximum energy (200 MeV). The recorded muons and photons have energies above 1 MeV but their fluencies are very low.

4. Conclusions
According to the results of this study, both for low and high energy primary protons, the most important components of the secondary radiation field are photons and neutrons. For the 500 MeV source term, muons, too, are an important component in the area between the interaction chamber and the beamdump. In that area, based on the upstream - downstream counting balance, we conclude that the spatial distribution is fairly isotropic for all components. The main sources of secondary radiation are the thick walls of the interaction chamber and the beamdump itself. The neutron component exhibits an isotropic spatial distribution on the energy range up to 200 keV at the TEST1 position and at higher energies the forward direction becomes predominant. This energy “threshold” shifts up toward 20 MeV for the TEST 2 and 3 positions. Photons and muons behave similarly: the higher the energy, the more predominant are the particles moving downstream. Regarding the shielding capacity of the beamdump, it is easily observed that the safest areas for the more sensitive equipment are behind the beamdump (between the crossing pipes) and in its shade cone from the south side.

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