Bremsstrahlung production with high-intensity laser matter interactions and applications

J Galy\textsuperscript{1}, M Maučec\textsuperscript{2,3}, D J Hamilton\textsuperscript{1}, R Edwards\textsuperscript{4} and J Magill\textsuperscript{1}

\textsuperscript{1} European Commission, DG-Joint Research Centre, Institute for Transuranium Elements, Karlsruhe, Germany
\textsuperscript{2} Nuclear Geophysics Division, Kernfysisch Versneller Instituut, Groningen, The Netherlands
\textsuperscript{3} Reactor Physics Division, Jožef Stefan Institute, Ljubljana, Slovenia
\textsuperscript{4} AWE plc Aldermaston, Plasma Physics Department, UK

E-mail: jean.galy@ec.europa.eu

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Abstract. In the last decade an evolution of experimental relativistic laser-plasma physics has led to highly sophisticated lasers, which are now able to generate ultra short pulses and can be focused to intensities in excess of $10^{21}$ W cm\textsuperscript{-2}, with more than 500 J on target. In the intense electric field of the laser focus, plasma with temperatures greater than 10 billion degrees can be generated. The laser interactions with solid or gas targets can generate collimated beams of highly energetic electrons and ions. Experiments utilizing high-intensity laser systems turn out to be an interesting and versatile source for radiation, high-energy particles and nuclear reactions, without recourse to large-scale facilities such as nuclear reactors or particle accelerators. The possibility of accelerating electrons to energies over 200 MeV in such early experiments led to the utilization of high-energy bremsstrahlung radiation in order to investigate laser-induced gamma reactions. Many experiments of this type have been reported in several laboratories worldwide. However, to our knowledge, no dedicated investigations have been reported with respect to the characterization of the generated bremsstrahlung in such experiments. As it is not experimentally feasible to measure directly a bremsstrahlung spectrum, we report in the present paper on a dedicated series of calculations on the generated bremsstrahlung distributions from two experimental electron spectra measured using the giant pulse VULCAN laser and a gas jet target. Potential applications are also investigated.
1. Introduction and background

As the power of lasers continues to increase, a new area of laser-induced nuclear reactions is emerging. The possibility of accelerating electrons in a focused laser field was first proposed by Feldman and Chiao [1] in 1971, although it was not until the mid to late eighties that the possibility of laser-induced fission using focused intensities as high as $10^{21} \text{ W cm}^{-2}$ was suggested [2]–[4]. Demonstration of the first photo-fission of uranium as a consequence of bremsstrahlung generation from a high-intensity laser was finally achieved in 2000 [5]–[7]. This laser-induced fission was later demonstrated on a thorium target and with a tabletop laser [8, 9]. More recently the first laser-induced transmutation of $^{129}$I, a key component of nuclear waste, was reported [10]–[12]. The ability to induce various kinds of nuclear reactions—such as activation, fission, fusion and transmutation—has therefore been demonstrated at several laboratories in recent years [5], [8]–[15], as the number of high-intensity lasers in the world has increased.

Several specific electron acceleration mechanisms have been identified in laser plasma interactions, with one mechanism dominating for a given set of laser and plasma conditions. In this study, we focus on electrons accelerated in an extended underdense plasma (where the electron density is less than the critical density), which can be created in a gas jet target by the laser pre-pulse. In such plasma conditions, it is possible to generate relativistic plasma waves through direct interactions with the main laser beam, leading to highly energetic, forward collimated electron beams. The first demonstration of such a beam utilized a high energy, subpicosecond laser [16] similar to the laser used in the present study. Since then, evolution of high intensity tabletop lasers with shorter pulse lengths (30 fs) has led to a series of exciting developments in electron acceleration. In this short-pulse regime, where the laser pulse length is smaller than the plasma wavelength, nonlinear relativistic plasma waves can be generated, which can in turn lead to forced growth of a wakefield plasma wave [17, 18], or formation of a plasma bubble due to self-focusing and channelling effects [19, 20]. Electron beams accelerated by both these mechanisms have proven to be of an extremely high quality, with the latter mechanism leading to the production of quasi-monochromatic beams.

The electrons accelerated in laser plasma interactions can then be slowed through interactions with nuclei in a material with high atomic number ($Z$), leading to the emission...
of bremsstrahlung photons, the energy of which takes a maximum value equal to that of the accelerated electrons. The generation of high-energy photons via the bremsstrahlung process allows studies of laser-induced gamma reactions in different materials. Thus the study of photo-reactions through the use of high intensity lasers follow a three step scheme: firstly, the generation of MeV electrons in the high-intensity laser plasma; secondly, conversion of these MeV electrons into MeV photons through the bremsstrahlung process in a high Z solid target; and finally, nuclear reactions induced by the high-energy bremsstrahlung photons. While the first step depends on the plasma physics associated with the characteristics of the laser, the two following steps relate solely to the nature of the generated electron spectra. In the present paper, we have focused our studies on the characterization of the bremsstrahlung spectrum created from experimental electron spectra measured at the VULCAN facility at the Rutherford Appleton Laboratory. We then investigate the potential applications offered by such an innovative laser-induced bremsstrahlung beam.

2. Bremsstrahlung converter studies and design

The spectrum of photon energies produced through the bremsstrahlung interaction is continuous. This photon energy ranges from zero up to a maximum value, which, for a monochromatic electron beam, is equal to the energy of the incident electron. It has been shown that the photon flux decreases monotonically with increasing photon energy down to zero at the maximum photon energy (the so-called bremsstrahlung endpoint). The spectrum also depends on the photon emission angle with respect to the direction of the incident electrons. With increasing angle, the intensity rapidly drops for all photon energies and the spectrum becomes softer because the decrease with emission angle is more pronounced for high-energy photons.

The conversion efficiency between electrons and bremsstrahlung photons depends on the electron energy, the converter material and converter thickness. For any given converter material, an optimum converter thickness exists whereby the bremsstrahlung efficiency reaches a maximum value. This optimum converter thickness corresponds approximately to the half-value of the electron range [21] in the particular material. However, because the optimum thickness is smaller than the electron range in this case, a large portion of the electron beam will be transmitted through the converter and can cause damage to the irradiation sample. Therefore, the thickness is usually chosen to be slightly greater than the maximum electron range at the highest energy used for activation. Furthermore, due to the strong Z-dependence of the conversion, the optimum target (in the case of a single layer) must consist of a high Z material. In all the calculations described in the present paper, tantalum has been used as a bremsstrahlung converter.

2.1. Bremsstrahlung converter optimization

All following calculations were performed using the Monte Carlo code MCNPX [22]. MCNPX uses the Bethe–Heitler [23] Born-approximation to sample bremsstrahlung photons. Formulae and theoretical approximations at the relevant level for MCNPX calculations can be found in the paper by Kotch and Motz [24]. A particular prescription appropriate to Monte Carlo calculations has been developed by Berger and Seltzer [21]. These data were converted to tables including bremsstrahlung production probabilities, photon energy distributions and photon angular distribution, and are used directly in MCNPX.
The conversion efficiency ($\varepsilon$) is often referred to as the fraction of kinetic energy of the incident electrons that emerges in the form of bremsstrahlung from a target of given thickness. In the simulations presented herewith, it is defined as

$$\varepsilon = \frac{\Phi_p^{\text{out}}}{\Phi_e^{\text{in}}},$$

where $\Phi_p^{\text{out}}$ represents the photon flux ($\text{cm}^{-2} \text{s}^{-1}$) through the rear surface of the Ta converter and $\Phi_e^{\text{in}}$ represents an incoming electron flux through the front surface.

The conversion efficiency, as defined above, was calculated by the standard MCNPX surface-averaged flux estimates. Preliminary calculations have been performed using mono-energetic beams in order to determine optimum thickness for the converter. The efficiency curves are thus parameterized for a set of converter thicknesses and initial electron energies. The statistical uncertainty associated with the integral values of the photon and electron flux within the converter were both below 0.5%, which means that the uncertainty of the estimated efficiency remains bound within 1%.

Although the interactions of high-intensity lasers with matter generate a continuous energy spectrum of electrons, in the following section the behaviour of bremsstrahlung for mono-energetic electron beams is first investigated. A previous study by Berger and Seltzer [21] has demonstrated that the bremsstrahlung efficiency in a tungsten target reaches its maximum for a target thickness between 0.4 and 0.5$r_0$ ($r_0$ being the mean range in the target material). The MCNPX calculations do, in fact, confirm this conclusion, as shown in figure 1. The mean range of the electrons was calculated using [25]. Table 1 gives calculated values for the range and estimated optimum converter thickness for the given electron energies.
Table 1. Electron mean range in tantalum (with a density of 16.6 g cm\(^{-3}\)) and optimum thickness bremsstrahlung converter for given electron energies (given as 0.5 multiplied by the range).

| Electron energy \(E_e\) (MeV) | Electron range \(\frac{g}{cm^2}\) | Estimated optimum thickness (mm) |
|--------------------------------|---------------------------------|--------------------------------|
| 1                              | 0.78                            | 0.24                           |
| 5                              | 3.25                            | 0.98                           |
| 10                             | 5.61                            | 1.69                           |
| 15                             | 7.51                            | 2.26                           |
| 20                             | 9.10                            | 2.75                           |
| 50                             | 15.5                            | 4.67                           |
| 100                            | 21.4                            | 6.45                           |
| 150                            | 25.2                            | 7.57                           |

2.2. Pair production and loss of photons in photo-reactions experiments

The intense electric field surrounding the nucleus can lead to the transformation of a photon into an electron–positron pair. The process, which is known as pair production, requires that the incoming photon energy is above a threshold of 1.022 MeV. This interaction strongly competes with gamma induced transmutation (either by fission or \((\gamma, \text{xn})\) reactions), particularly in the energy range of \(\sim 15–30\) MeV—the giant dipole resonance (GDR). In addition, the efficiency of photon-induced transmutation is severely limited by the absorption phenomena in the thick target of materials to transmute.

In a general manner, the cross-section of electron–positron pair creation is proportional to \(Z^2\) —the square of the atomic number of the nuclide—while that of the photonuclear cross-section is proportional to \(A\), the mass number of the nuclide. Therefore, photon beams will be more effectively used for nuclear transmutation in light nuclei. To calculate the approximate maximum yield of direct transmutation \(Y_\gamma\) (where \(N_\gamma = 1/Y_\gamma\) is the average number of photons needed to transmute one nucleus) one can assume that the photons are all absorbed in a target of a given thickness. This photon absorption around the 20 MeV energy range is essentially due to pair production, which doesn’t lead to any nuclear transmutation.

If one assumes that the target is made up of only one type of nucleus to be transmuted, it is easily demonstrated that the maximum yield per photon is equal to

\[
Y_\gamma = \frac{\sigma_{\gamma,n}}{\sigma_{\gamma,e^+e^-} + \sigma_{\gamma,n}} \approx \frac{\sigma_{\gamma,n}}{\sigma_{\gamma,e^+e^-}}.
\]

Figure 2 shows a comparison between the photofission and the pair production cross-sections for uranium (the data come from \([26, 27]\)). The pair production cross-section around 20 MeV for an atom of atomic number \(Z\) is approximately equal to \(3.2 \times 10^{-27} Z^2\) (cm\(^2\)), whereas the energy integrated GDR photon-nuclear cross-section is approximately given by

\[
\sigma = \int \sigma(E) \, dE \sim 0.002 A \text{ (MeV barn)},
\]

where \(A\) is the atomic mass number.

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Thus the number of photons required to transmute a nucleus can be estimated in the GDR region by

\[ N_\gamma \approx 1.6 \frac{Z^2}{A}. \]

In the case of U\textsuperscript{238}, it turns out that \( N_\gamma = 57 \) photons. This is, of course, an estimate of the integrated value over the GDR. The indirect transmutation/fission by photons, which utilize photo-produced neutrons, may diminish the number of required photons required, but not significantly.

3. Investigation on VULCAN spectra and applications

In the following, we report on an investigation based on laser electron spectra measured at the VULCAN petawatt facility in the Rutherford Appleton facility. To our knowledge, no systematic investigation to characterize the bremsstrahlung produced with high-intensity lasers has been reported. It should be noted, however, that a GEANT \[28\] calculation of the bremsstrahlung energy distribution from a table top high-intensity laser has been presented in \[9\].

VULCAN is the main high power laser facility operated by the Central Laser Facility (CLF) at the Rutherford Appleton Laboratory, UK. It is a powerful Nd:glass laser system originally designed to deliver up to 2.6 kJ of laser energy in nanosecond pulses and over 100 TW power in sub-picosecond pulses at 1054 nm. Those characteristics make it possible to produce intensities of up to \(10^{20}\) W cm\(^{-2}\). Recently, VULCAN’s ultra-short pulse beam has been increased to 500 J in a pulse of 500 fs duration, resulting in a power on target of 1 petawatt \((10^{15}\) Watts). With the use of new adaptive optics to correct wavefront errors, the VULCAN beam can now be focused to a near diffraction limited focal spot, producing irradiance on target of \(10^{21}\) W cm\(^{-2}\).
In the present paper, characterization of the produced bremsstrahlung spectra is based on two experimental electron spectra measured at the VULCAN petawatt laser, running at $10^{21}$ W cm$^{-2}$. The electrons in these shots were produced and accelerated in a plasma interaction of the laser beam in a gas jet. A high density gas jet nozzle with a critical diameter of 0.5 mm and an exit diameter of 1 mm was used to generate a supersonic gas flow with a constant density [29]. The pressure material for both shots was helium. The first shot we considered had a pulse length of 0.7 ps, an energy of 290 J on target and a gas backing pressure of 61.4 bar; whilst the second shot had a pulse length of 1.2 ps, the same energy on target of 290 J and a lower backing pressure of 49.9 bar. Commissioning experiments on the VULCAN petawatt laser found an on-axis focal spot diameter varying between 5–15 µm (full width half maximum, FWHM).

The electron spectra were measured on-axis using an electromagnetic spectrometer with a maximum momentum acceptance of 1 GeV c$^{-1}$. The focal plane detector for the spectrometer was a Fuji image plate, which utilizes a process called photo-stimulated luminescence (PSL) to produce an image of the number of electrons hits at each point on the plate. Europium atoms in the active layer of the plate are excited into a metastable state when they absorb energy from ionizing radiation, which is incident on the plate. The scanning is performed by illuminating the plate with a HeNe laser and recording the amount of light emitted with a photo-multiplier. The relationship between PSL intensity and energy deposited in the plate is close to linear. A study of the performance of image plates in high energy electron detection has recently been performed [30]. The authors report a good linear response over five orders of magnitude, a sensitivity of $10^3$ high-energy electrons per pixel and a corresponding position resolution of 200 microns. These properties give rise to a momentum resolution of the electron spectrometer ($\Delta p/p$) of around 2.5% (FWHM). The two electron spectra are plotted in figure 3; it is interesting to note that electrons are more energetic in short pulse systems, as a shorter pulse duration implies a higher intensity on target, and therefore a larger acceleration potential.

Figure 3. Experimental measurements of the electron distributions from a single shot of the VULCAN laser for pulses of 1.2 ps and 700 fs measured with the help of a magnetic electron spectrometer specifically developed [36] to look for high energy electrons.
3.1. Bremsstrahlung conversion

The electron spectrum is usually described by

$$\frac{dN_e}{dE_e} \approx v_0 E \exp(E/T),$$

where $T$ is the hot electron temperature associated with the electron spectrum and $v_0$ is a normalization constant.

Neglecting changes in the electron bunch during its propagation in the target one can integrate the approximate expression for the integrated-over-angle bremsstrahlung cross-section from [10, 31]

$$\frac{d\sigma}{dE_\gamma} \approx aZ^2(E_\gamma^{-1} - bE_e^{-1}),$$

over the electron spectrum to obtain [31, 32]

$$\frac{dN_\gamma}{dE_\gamma} \approx n_a l \int_{E_0}^{E_\gamma} \frac{d\sigma}{dE_\gamma} \times \frac{dN_e}{dE_e} dE_e = Rf_\gamma(E_\gamma),$$

with

$$R = T n_a a Z^2 v_0,$$

and

$$f_\gamma(E_\gamma) = \left(1 - b + \frac{T}{E_\gamma}ight) e^{-\frac{E_0}{E_\gamma}} + \left( b - \frac{E_0}{E_\gamma} - \frac{T}{E_\gamma} \right) e^{-\frac{E_0}{E_\gamma}},$$

where $dN/dE_\gamma$ is the number of bremsstrahlung photons radiated in 1 MeV interval at the photon energy $E_\gamma$; $E_0$ is the cut-off of the electron spectrum; $Z$, $n_a$ and one are the atomic number, the atomic density, and the thickness of the target, respectively; and $a \approx 11$ mbarn, $b \approx 0.83$.

Fitting of the VULCAN electron spectra gave an electron temperature of $T_1 = 19$ MeV and $T_2 = 10.4$ MeV for the 0.7 ps and 1.2 ps shots respectively. The converter is chosen to be tantalum due to the strong $Z$ dependence of the bremsstrahlung conversion ($Z = 73$, $n_a \approx 5.7 \times 10^{22}$ cm$^{-3}$). It is then possible to estimate the number of photons produced: $5.6 \times 10^{11}$ for the 700 fs spectrum and $8.8 \times 10^{11}$ for the 1.2 ps spectrum. It is quite instructive to compare these relatively simple estimates with the corresponding number of photons going through the integrated front surface of the uranium target as calculated in MCNPX, namely $6.9 \times 10^{11}$ photons for the 700 fs spectrum and $1.2 \times 10^{12}$ photons for the 1 ps spectrum.

As in the mono-energetic case described above, a bremsstrahlung conversion efficiency study was carried out, with the results shown in figure 4. Based on these results we have chosen a thickness of 3 mm for the Ta bremsstrahlung converter in all of the following calculations. Furthermore, we have assumed a converter cross section of $3 \text{ cm} \times 3 \text{ cm}$, which corresponds to the Ta converter that was actually used in our previous experiments on laser bremsstrahlung generation for laser-induced nuclear reaction studies.

Bremsstrahlung calculations with MCNPX have been performed and are reported in figure 5 for the energy distribution of the outgoing photons emerging from the back of the converter.
Furthermore, in order to estimate any systematic uncertainty that might arise through the use of a particular model these calculations have been repeated with the GEANT [28] Monte Carlo code, which uses the same bremsstrahlung parameterization as MCNPX. The bremsstrahlung distributions generated from the two VULCAN electron spectra in the GEANT calculations are shown in figure 6, while a comparison between the GEANT and MCNPX photon spectra is shown in figure 7. One immediately sees that the results from the two Monte Carlo codes are identical within overall statistical uncertainty. This provides confidence in the validity of the

![Figure 4](http://www.njp.org/bremsstrahlung.png)

**Figure 4.** Bremsstrahlung efficiency curves for the VULCAN generated electron spectra incident perpendicularly on the Ta target.

![Figure 5](http://www.njp.org/bremsstrahlung-energy.png)

**Figure 5.** Calculated Bremsstrahlung energy distribution for the two experimentally measured VULCAN spectra with the MCNPX code. The plot represents the flux through the back surface of the Ta converter.

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Figure 6. Calculated Bremsstrahlung energy distribution for the two experimentally measured VULCAN spectra using the GEANT code.

Figure 7. MCNPX and GEANT bremsstrahlung calculation comparisons for the two given VULCAN experimental spectra.
MCNPX model that has been developed and shows that no systematic uncertainty is introduced by the choice of model.

3.2. Induced nuclear reactions by the VULCAN bremsstrahlung spectra

The ability to induce different kinds of nuclear reactions with high-intensity lasers, such as activation, fission, fusion and transmutation, has been demonstrated in recent years at several laboratories [5, 6], [9]–[14], [33]. The first photo-fission of uranium by means of bremsstrahlung from laser produced plasma was achieved in 2000 [5]. This was later extended to $^{232}$Th, and laser-induced fission was also demonstrated using a tabletop laser [33]. In 2003, the first laser-induced transmutation of $^{129}$I—a key contributor to long-lived radiotoxicity in nuclear waste—was reported [10]–[12]. $^{129}$I with a half-life of 15.7 million years was transmuted into $^{128}$I with a half-life of 25 min through a ($\gamma$, n) reaction using laser-generated bremsstrahlung and the integral cross-section value for the reaction was determined for the first time. More recently, Pb(p,xn) reactions have been investigated using MeV protons accelerated in ultra-intense VULCAN laser interactions [34].

The possibility of accelerating electrons to hundreds of MeV in the plasma interactions has driven an enthusiasm in investigating laser generated bremsstrahlung nuclear reactions. Furthermore, the studies of actinide fission or transmutation of long lived fission products can be easily set up because samples can remain encapsulated—to avoid any risk of nuclear material release hazards—during irradiation with bremsstrahlung photons. These laser-induced gamma nuclear reactions have many possible applications, including

1. the production of medical isotopes through transmutation;
2. the studies of alternative research paths to classical reactor neutron-induced reactions for transmutation purposes;
3. the measurement of nuclear data;
4. the detection of illicit radioactive material.

It should be noted that the first two applications involve nuclear transmutation in the strict sense of the word: creating one nuclide from another through nuclear reactions. We are not discussing here the transmutation of nuclear waste [35], which is an industrial scale process involving fast nuclear reactors or accelerator-driven systems, that has been proposed for the reduction of the long-term radiotoxicity of the waste. Indeed, the transmutation rates achievable in experiments with high-intensity laser systems are currently many orders of magnitude lower than those required even to produce milligram quantities of radionuclides for medical applications. Moreover, the latter possibility also requires significant advances in laser technology to be a practical option. It has nonetheless been proposed as a novel non-destructive assay technique, involving the future deployment of compact, high-intensity lasers and neutron detectors at border portals, in order to induce and detect photo-fission reactions in illicit nuclear material.

In the present paper, we study the nuclear reactions occurring in a piece of depleted uranium with a thickness of 3 mm, $\varnothing$ 1 cm. This is actually the size of uranium samples used in previous laser-induced fission experiments at the VULCAN terawatt facility and at the University of Jena, through Institute for Transuranium Elements (ITU, Karlsruhe, Germany) collaborations on high-intensity laser-induced nuclear reaction studies. Depleted uranium has a density of 19.05 g cm$^{-3}$.
Table 2. Reaction rates obtained in the Ta and U targets.

|                  | Photo-electric absorption (per electron) | Pair production (per electron) | Photofission ($\gamma, f$) in secondary U target (per electron) |
|------------------|------------------------------------------|--------------------------------|---------------------------------------------------------------|
|                  | Ta target                                | U Target                       | Ta target                                | U Target                       | U-235 | U-238     |
| 700 fs           | 1.88E-01                                 | 1.74E-01                       | 1.53E-01                                 | 4.44E-02                       | 1.38E-06 | 3.62E-04 |
| >1 ps            | 1.69E-01                                 | 1.09E-01                       | 9.49E-02                                 | 2.45E-02                       | 6.54E-07 | 1.70E-04 |

Table 3. Total number of fissions obtained with the VULCAN spectra. Numbers are calculated assuming a solid angle acceptance of 4 $\mu$sr for the electron spectrometer.

|                  | Total number of electrons | Number of incoming photon in the surface of the uranium target | Total number of pair production in U target | Total number of fission in U target |
|------------------|---------------------------|--------------------------------------------------------------|--------------------------------------------|----------------------------------|
| 700 fs           | 8.1E+10                   | 6.9E+11                                                      | 3.6E+09                                   | 2.9E+07                          |
| >1 ps            | 1.9E+11                   | 1.2E+12                                                      | 4.7E+09                                   | 3.2E+07                          |

and its composition is the following: 99.8% of $^{238}$U, 0.0003% of $^{236}$U, 0.2% of $^{235}$U and 0.001% of $^{234}$U. In the calculations, we have assumed that the electrons are accelerated in a gas jet target located upstream of the bremsstrahlung converter. In a recent Rutherford Appleton Laboratory (RAL, Chilton, UK) report [36] Mangles and collaborators report that the square acceptance of the PSL spectrometer is $2 \times 2$ m rad. We have used this value for the solid angle (of $4 \times 10^{-6}$ sr) for our activation/production calculations.

In table 2, one can see the relative number of photo-induced reactions (photo-electric absorption, electron–positron pair production and photo-fission reactions) per incident electron in both the tantalum converter and the uranium target. We have separated the relative isotopic contributions to the total number of photo-fissions in the uranium target. Table 3, on the other hand, gives the absolute numbers for pair production and the number of fissions in the uranium target alone. One can see that the pair production rate is about two orders of magnitude higher than the fission rate. This can be explained by the comparatively high pair production cross-section, which is actually increasing with energy. As an example: at 14 MeV the $^{238}$U($\gamma, f$) cross-section is equal to 175 mb, whilst the corresponding pair production cross-section is equal to 18.9 barn. Furthermore, at energies immediately above the GDR the $^{238}$U($\gamma, x$) reaction cross-section becomes much lower, but the pair production cross-section remains high.

In table 4, the total number of fission events that have been calculated based on these two VULCAN shots, compared with a series of experimentally measured fission rates at the Laboratoire d’Optique Appliquée (LOA, Palaiseau, France) [9], Jena [37], RAL [5] and Lawrence Livermore National Laboratory (LLNL, Livermore, USA) [6] facilities, are shown. All these rates have been normalized to 1 J of laser energy. These rates are presented in order to highlight improvements in the ability to induce photonuclear reactions as laser technology and the associated electron acceleration mechanisms continue to improve. Indeed, one needs to
Table 4. Comparison of experimental laser-induced-fission rates for different laser systems and the present VULCAN calculations.

| Laser  | Wavelength ($\mu$m) | Pulse length (fs) | Energy per pulse (J) | Intensity (W cm$^{-2}$) | Fission rate in uranium per 1 J |
|--------|---------------------|-------------------|----------------------|-------------------------|--------------------------------|
| LOA [9] | 0.8                 | 30                | 0.5                  | $2 \times 10^{19}$       | $4.6 \times 10^4$               |
| Jena [37] | 0.8              | 80                | 0.26                 | $4 \times 10^{19}$       | $4 \times 10^2$                 |
| RAL [5]  | 1.0                 | 1000              | 17.5                 | $10^9$                   | $6 \times 10^5$                 |
| LLNL [6] | 1.0                 | 450               | 250                  | $10^{20}$                | $7 \times 10^4$                 |
| VULCAN  | 1.0                 | 700               | 290                  | $2 \times 10^{20}$       | $1 \times 10^5$                 |
| Calculations | 1.0            | 1000              | 290                  | $2 \times 10^{20}$       | $1.1 \times 10^5$               |

exercise caution when making any quantitative comparisons between the numbers presented in table 4, as all experimental rates have been measured with lasers incident on overdense (solid) targets, while the rates calculated in the present study are based on the VULCAN laser incident on an underdense (gas jet) target. The electron acceleration mechanisms, and therefore the electron spectra, in solid and gas jet targets are significantly different. It is interesting to note, nevertheless, that the calculated fission rates are close to the NOVA laser experiment on a solid target [6]—the only petawatt laser which has produced fission on uranium thus far, and which has a similar specification to the new petawatt upgrade of VULCAN.

3.3. Neutron production

Multi-terawatt and petawatt lasers are now considered as potentially powerful pulsed neutrons sources. In previous studies [38], protons with energies up to 58 MeV have been observed and an energy conversion efficiency—from laser light to proton—of 12% has been obtained. Taking into account the high proton energies, high laser to proton efficiency and short pulse length, the laser-induced proton reactions—via (p,xn) and/or (p,f) channels—appear to be a promising route towards novel fast compact neutron sources. Due to the relatively high proton generation efficiency on solid targets, such sources could be significantly stronger than neutron sources which utilize the interaction of femtosecond laser pulses with deuterium clusters, capable of yields up to $10^5$ fusion neutrons per joule of incident laser energy. Nowadays, neutron sources have an extremely broad range of applications in science and technology (e.g. neutron activation analysis, nuclear radiography, nuclear geophysics and more). The neutron spectra and flux levels required for each application depend on the specific characteristics of the application and need to be well defined and characterized for routine use. In all cases, a compact mobile, energy efficient neutron source with a low contamination risk would be of great advantage in the above mentioned technology fields. These calculations based on results obtained from the original VULCAN electron spectra will be the basis for estimating the fast neutron production capabilities of current and future table-top laser systems.

In a previous lead experiment at RAL [34, 39], we produced and measured (via $\gamma$-spectroscopy) more than $1.2 \times 10^9$ bismuth atoms through (p,xn) reactions. In order to produce this number of Bi atoms, more than $1.6 \times 10^9$ neutrons had to be released in (p,xn) reactions on natural lead. Since we have to take into account neutrons released in the production of the long lived isotopes $^{207}$Bi and $^{208}$Bi, we may assume a value of $2 \times 10^9$ neutrons released per laser shot,
Table 5. Neutron production in the uranium target with the VULCAN spectra (all numbers are given per cm$^3$ and per incoming electron).

| Energy | Number of neutrons produced by fission | Number of neutrons produced by ($\gamma$, xn) reactions | Total number of neutrons produced |
|--------|---------------------------------------|--------------------------------------------------|---------------------------------|
| 1.2 ps | 7.2292E-04                            | 1.0193E-03                                       | 3.4374E-3                      |
| 700 fs | 1.5372E-03                            | 2.4204E-03                                       | 7.6834E-3                      |

Figure 8. Calculated neutron spectra from photo-nuclear reactions in uranium for both VULCAN sources. The numbers represent the neutron flux (per cm$^2$ per second per starting particle), averaged over the surfaces of the uranium plate.

leading to a neutron yield of $5 \times 10^6$ neutrons per joule of incident laser energy, without taking into account the proton beam in front of the primary target, which could double the neutron yield. The paper by Žagar et al [39] has shown that the highly efficient conversion of laser light into fast protons, achieved with irradiation of a thin solid target, has opened a new way of generating pulsed neutron sources. We have demonstrated that, in the near future, due to the fast evolution of laser technology, tabletop lasers have the potential to become effective, flexible and cheap neutron sources, able to compete with traditional neutron sources.

In the present calculations, neutron production from fission and ($\gamma$, xn) (up to two neutrons produced per reaction, which is the limit of the known cross-sections) has been assessed. Table 5 summarizes the neutron production capabilities taking into account the fission neutrons and the ($\gamma$, xn) neutrons (in our calculations we limit the production to two neutrons per reaction due to the lack of available cross-sections). It is interesting to note that the 700 fs spectrum produces about twice the number of neutrons per incident electron compared with the 1.2 ps spectrum. An energy distribution for the produced neutrons is given in figure 8. As expected, the neutrons are distributed through a Maxwellian shape with fast energy (peaked around 2 MeV).

The total number of neutrons produced per shot (about $6 \times 10^8$) can be compared with the previous attempts to measure the laser produced neutron yield in VULCAN: $2 \times 10^9$ neutrons.
Table 6. Positron sources which are currently available.

| Positron source | Maximum positron flux (s$^{-1}$) |
|-----------------|----------------------------------|
| **(1) Long-lived $\beta^+$ sources** | |
| $^{22}$Na (Specific activity: $2.31 \times 10^{14}$ Bq g$^{-1}$) | $10^9$ |
| $^{58}$Co (Specific activity: $1.18 \times 10^{15}$ Bq g$^{-1}$) | $10^9$ |
| **(2) Short-lived $\beta^+$ sources** | |
| $^{64}$Cu (n capture at the high flux beam reactor BNL) | $10^7$ |
| $^{13}$N (1.5 MeV D beam at Brandeis University) | $10^7$ |
| $^{114}$Cd (n capture at Garching reactor FRM-II) | $10^{10}$ |
| **(3) Electron Linac sources** | |
| Oak Ridge ORELA (180 MeV 60 kW) | $10^8$ |
| LLNL (100 MeV 45 kW) | $10^{10}$ |
| **(4) Pair production in reactor** | |
| HOR reactor of Delft University of Technology | $10^8$ |

per shot using (p,xn) reactions [39]; $10^{10}$ neutrons per shot using Zn(p,xn) reactions [40]; and in the latest paper the authors have demonstrated that $4 \times 10^{10}$ neutron per shot can be achieved using Li(p,n) reactions. It is apparent that laser bremsstrahlung neutron production is not the most effective way of producing fast neutrons. The efficiency of laser light to photon via bremsstrahlung is lower than one percent, while the efficiency of laser light to proton can reach up to 10%. In addition, cross-sections are higher for (p,xn) reactions than they are for ($\gamma$, f) or ($\gamma$, xn) reactions. On the other hand, one could think of a two step transmutation device: a first target would be irradiated by laser-induced bremsstrahlung—this could consist of fission products, where neutron transmutation is limited or inefficient—and the produced neutrons could be collimated to irradiate a second target to be transmuted, such as actinides. The numbers we have calculated can, nevertheless, be compared with other portable neutron generators or spontaneous fission sources, which have typical source strengths of around $10^{8}$ to $10^{10}$ neutrons s$^{-1}$ and $10^{10}$ neutrons cm$^{-2}$ s$^{-1}$, respectively. Traditional reactors produce a flux of neutrons ranging from $10^7$ to $10^{13}$ neutrons s$^{-1}$, while high flux reactors can achieve flux up to $10^{14}$ neutrons cm$^{-2}$ s$^{-1}$.

3.4. Positron production

Positron sources are today used in several applications in various fields, such as positron annihilation and Doppler broadening spectroscopy in material science or positron spectroscopy in fundamental research. Low energy positrons are now being used for many of these applications, including studies of electron–positron plasma phenomena [41], atomic and molecular physics, anti-hydrogen formation [42], modelling of astrophysical processes [43], and the characterization of materials [44]. Several positron sources are currently available, and some of the most common ones are summarized in table 6.

As bremsstrahlung photons propagate through a heavy target—in our particular case tantalum and uranium targets—they will produce positrons through the pair production process discussed above. The positron that is produced will quickly annihilate with an atomic electron causing the production of two 0.511 MeV photons. By characterizing these gamma rays through spectroscopy, the properties of the electron distribution within the material of interest can be
determined. The annihilation rate gives the density of the electrons, and the energy and angular distribution of the annihilation photons supplies information about electron momentum.

As in the previous sections, we have calculated the positron production capabilities of high-intensity lasers by using the original measured VULCAN spectra emerging from the back of the tantalum and uranium targets. Results are presented in table 7. A previous paper [45] on the positron production with a high intensity laser—the former NOVA laser at LLNL operating at $3 \times 10^{20}$ W cm$^{-2}$—reports a positron production of $10^{-4}$ per electron. As with the fission rate comparison given in table 4, it is important to note here that the NOVA experiments on positron production utilized electron acceleration in an overdense (solid) target, giving rise to a markedly different electron spectrum compared to the VULCAN data on which our estimate are based. It is still instructive to compare the NOVA results with what we have calculated: that the 700 fs VULCAN spectrum could produce $1.5 \times 10^{-2}$ positron per electron, which in turn leads to $\sim 10^9$ positrons per shot.

To put this into perspective, a comparison between the traditional positron sources presented in table 6 and laser-induced positrons can be made. Electron linac sources and positrons generated by pair production inside reactor beam can generate about $\sim 10^8$ s$^{-1}$ slow positrons, which is approximately 1000 times more intense than the commonly employed positron beams that rely on a radioisotope for positron generation—even so, sources of $^{22}$Na of 3–20 mCi (about $\sim 10^8$ Bq) are available. It has been calculated that the VULCAN laser could be capable of producing approximately $10^9$ positrons per shot. This value can thus be directly compared to strengths of positron sources, even if one has to take into account the low repetition rate of the giant pulse laser ($\sim$ one shot every 30 min). In addition, the development of terawatt tabletop lasers, with actual repetition rates of 10 Hz, and the current fast evolution in laser technology is leading to the emergence of lasers with higher repetition rates and higher intensities. Indications that future laser systems will reach intensities well beyond $10^{21}$ W cm$^{-2}$ in the next decade have been reported [46, 47].

4. Conclusion

The dramatic improvements in laser technology that have occurred during the last decade have resulted in intensities reaching up to $10^{21}$ W cm$^{-2}$. At these intensities, the electron quiver energy in the laser field is fully relativistic and leads to the generation of high-intensity beams of energetic gamma rays—via bremsstrahlung production—as well as protons, neutrons and heavy ions. The versatility of the laser-induced radiation beams make these lasers effective tools for studying nuclear reactions without the need for large infrastructures such as electron accelerators or nuclear research reactors.

Table 7. Positron production through the back of the Ta converter and the U target generated by the two experimental VULCAN spectrum.

| Number of positrons (per electron) | Ta converter | U target |
|-----------------------------------|--------------|----------|
| 700 fs                            | 9.69E-04 ± 0.0203 | 1.53E-02 ± 0.0153 |
| >1 ps                             | 5.01E-04 ± 0.0244 | 5.59E-03 ± 0.0219 |
Photonuclear reactions with lasers were the first to be experimentally measured for several reasons: the acceleration of high-energy electrons in the laser field was one of the first observations in this field; these electrons can then be used to produce bremsstrahlung photons with a suitable converter. In addition, a renewed interest in photonuclear reactions has developed in various laboratories around the world in recent years. Several applications are foreseen: radioactive beam production, sources of neutrons, medical isotope production, transmutation and nuclear material production. Photo-fission is expected to play a significant role. High-intensity giant pulse and tabletop lasers have been used recently to demonstrate nuclear fission on $^{238}\text{U}$ and $^{232}\text{Th}$ targets and transmutation of the long-lived fission product $^{129}\text{I}$.

However, although experimental demonstration of laser-induced nuclear reactions has been widely reported, to our knowledge, no systematic investigation of the produced bremsstrahlung and reaction rates has ever been described in the literature. For the first time, therefore, we have described a dedicated survey with electromagnetic transport calculations of the bremsstrahlung produced by the VULCAN laser on an underdense target. From two experimentally measured electron spectra, we have performed MCNPX Monte Carlo transport calculations to characterize the produced bremsstrahlung spectra and to estimate the number of fission reactions in a depleted uranium secondary target. The fission rates that have been obtained were compared to previous reported experimental studies, with which they agreed. Laser-induced transmutation is not presented as a direct competitor to classical neutron transmutation, but as an alternative path of investigation on which the flexible use of the laser can be an important benefit for research. On the other hand, lasers could become very useful tools for nuclear data measurements, as well as valuable tools in the battle to prevent the illicit trafficking of nuclear material.

The predominant process affecting high-energy bremsstrahlung photons has been shown to be pair production, which has a large cross-section at energies higher than 10 MeV. For the photo-nuclear reactions of interest, it is a process through which efficiency is lost, but it can be put to use as a positron source for applications such as positron annihilation spectroscopy. We have calculated that in the VULCAN experiment, we can produce $10^9$ positrons per shot. VULCAN is, at the present moment in time, the most powerful laser available worldwide. However, with the current fast evolution of laser technology, laser systems with high repetition rates (such as table-top laser systems, currently working at 10 Hz with intensities up to $10^{20}$ W cm$^{-2}$) and possibly higher intensities are emerging. One can expect that these systems can be put to use as strong, possibly compact positron sources.

References

[1] Feldman M J and Chiao R Y 1971 Phys. Rev. A 4 352
[2] Rhodes C K 1985 Science 264 1345
[3] Lynn J E 1988 Nature 333 116
[4] Boyer K, Luk T S and Rhodes C K 1988 Phys. Rev. Lett. 60 557
[5] Ledingham K W D et al 2000 Phys. Rev. Lett. 84 899
[6] Cowan T E et al 2000 Phys. Rev. Lett. 84 903
[7] Unstadter D 2000 Nature 404 239
[8] Schwoerer H et al 2003 Europhys. Lett. 61 47
[9] Malka G et al 2002 Phys. Rev. E 66 66402
[10] Magill J et al 2003 Appl. Phys. B 77 387
[11] Ledingham K W D et al 2003 J. Phys. D: Appl. Phys. 36 L79
[12] Ewald F et al 2003 Plasma Phys. Control. Fusion 45 1

New Journal of Physics 9 (2007) 23 (http://www.njp.org/)
[13] Ledingham K W D, McKenna P and Singhal R P 2003 Science 300 (5622) 1107
[14] Umstadter D 2000 Nature 404 239
[15] Magill J and Galy J 2005 Radioactivity, Radionuclides and Radiation (Berlin: Springer)
[16] Modena A et al 1995 Nature 377 606
[17] Malka V et al 2002 Science 298 1596
[18] Najmudin Z et al 2003 Phys. Plasmas 10 2071
[19] Faure J et al 2004 Nature 431 541
[20] Mangles S P D et al 2004 Nature 431 535
[21] Berger M J and Seltzer S M 1970 Phys. Rev. C 2 621
[22] Walter L S 2005 MCNPX User’s Manual LA-CP-05-0369 (Los Alamos: LANL)
[23] Bether H A and Heitler W 1934 Proc. R. Soc. (London) A 146 83
[24] Koch H W and Motz J W 1959 Rev. Mod. Phys. 31 920
[25] Magill J 2003 Nuclides.net: An Integrated Environment for Computations on Radionuclides and Their Radiation (Berlin: Springer)
[26] Arruda Neto J D T et al 1976 Phys. Rev. C 14
[27] Saloman E B, Hubbell J H and Scofield J H 1988 At. Data Nucl. Data Tables 38 1
[28] Agostinelli S et al 2003 Nucl. Instrum. Methods Phys. Res. A 506 250
[29] Semushin S and Malka V 2001 Rev. Sci. Instrum. 72 2961
[30] Tanaka K A, Takahashi T and Okuda S 2005 Rev. Sci. Instrum. 76 013507
[31] Findlay D J S 1989 Nucl. Instrum. Methods Phys. Res. A 276 598
[32] Shkolnikov P L et al 1997 Appl. Phys. Lett. 71 3471
[33] Schwoerer H et al 2003 Europhys. Lett. 61 47
[34] McKenna P et al 2005 Phys. Rev. Lett. 94
[35] Bowman C D and Magill J 2006 Lect. Notes Phys. 694 169
[36] Mangles S P D et al 2003 Annual Report 2002/2003 RAL, Central Laser Facility (Chilton: RAL) p 17
[37] Ewald F 2004 PhD Thesis Institute for optics and quantum electronics, Friedrich-Schiller-University, Jena
[38] Snively R A et al 2000 Phys. Rev. Lett. 85 2945
[39] Zagar T et al 2005 New J. Phys. 7 253
[40] Yang J et al 2004 J. Appl. Phys. 96 6912
[41] Greaves R G and Surko C M 1997 Phys. Plasma 4 1528
[42] Amoretti M et al 2002 Nature 419 456
[43] Iwata K, Greaves R G and Surko C M 1996 Can. J. Phys. 1 407
[44] Schultz P J and Lynn K G 1988 Rev. Mod. Phys. 60 701
[45] Cowan T E et al 2000 Nucl. Instrum. Methods Phys. Res. A 455 130
[46] Tajima T and Mourou G 2002 Phys. Rev. ST 5 031301
[47] Ditmire T et al 2004 Radiat. Phys. Chem. 70 535