Diagnosis of high-energy photon emission during imaging experiments using copper activation techniques.

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Introduction

A collaborative experiment was carried out at the Rutherford Appleton Laboratory in February 2013 to quantify and characterise the ionising radiation produced when the Vulcan Petawatt laser beam is incident on various target materials.

It is well-known that laser-target interactions can produce ionising radiation. One aim of this experiment was to characterise radiation beam profile for a range of target types. This will aid target selection in future experiments.

Stable copper can become activated by ionising radiation in a (γ,n) reaction, known as photonuclear activation. The $^{63}Cu(\gamma,n)^{62}Cu$ reaction was used to measure the induced radioactivity from the laser interactions. Blocks of copper (dimensions 50x40x10mm) were used to profile the radiation beam. The $^{63}Cu(\gamma,n)^{62}Cu$ reaction has a decay mode of a positron (β^+) with an abundance of ~69% and a half-life of ~9.7 minutes.

Using an array of copper blocks allows the activation at different points in space to be estimated. This method was used to show changes in activity when various laser targets were used. These target materials included plastic, aluminium, copper and tantalum in thicknesses from 0.1mm to 25mm.

Experimental setup

Initially, a linear array of six copper blocks was placed by the flange outside the chamber as seen in Figure 1.

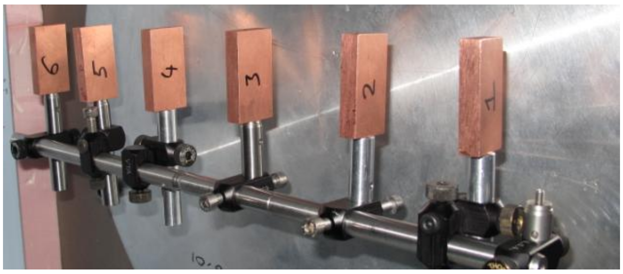

Figure 1: A linear array of six copper blocks outside the chamber.

Measurements were later made with eight copper blocks arranged in a curved array inside the chamber around the laser target (Figure 2). The copper blocks were placed around the target by hand (so the angle positions w.r.t the target are approximate).

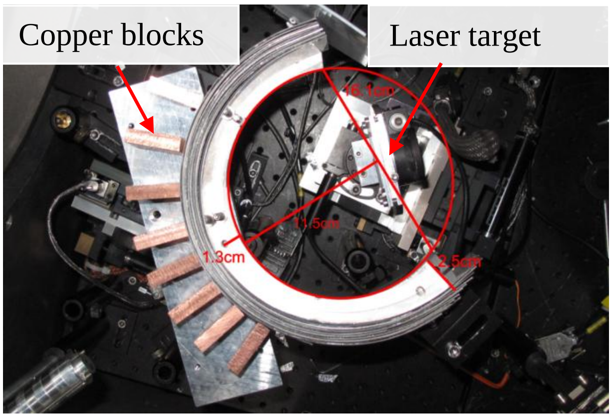

Figure 2: A curved array of eight copper blocks inside the chamber and around the laser target.

Following a laser shot, the copper blocks were removed from the target area and individually read using an energy resolving liquid nitrogen cooled hyper-pure germanium (HP:Ge) spectrometer. Due to the short half-life of this decay mode, copper blocks were placed onto the spectrometer and readings taken for approximately two minutes. This improves the results of the blocks being read later. The number of counts from the β^+ emission in the 511keV photopeak was provided by the spectrometer software (Figure 3). This was repeated for each block, allowing the activity at each position from the laser target to be plotted.

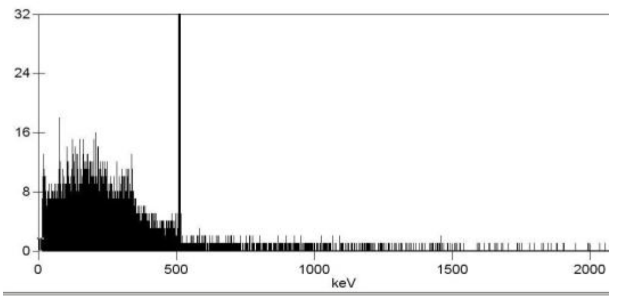

Figure 3: A HP:Ge detector reading of a copper block showing the 511keV activation line.

In some cases, it was not possible to discern counts from the background (in cases where there was insufficient activation remaining), so data-points are missing from some results.

There is a trade-off when determining where to place the copper blocks. They are closer to the laser target inside the laser chamber, however, as the laser chamber is under vacuum, the chamber has to be ‘let up’ from vacuum before the copper blocks can be retrieved. This process takes about 15 minutes and means that three half-lives can elapse before each copper block was read for activity. Outside of the chamber however, the copper blocks can be removed and read in the spectrometer more quickly, as there is no delay in waiting for the chamber to be ‘let up’. Accounting for this trade-off, increased activities were observed when the copper blocks were placed inside the laser chamber (accounting for the time difference).

As the decay mode of interest has a short half-life, the time difference between the starting each scan becomes important. The time duration from the laser shot to the reading of each block was factored in, to give an initial activity (A_0) which accounts for:

1. detector efficiency (taken as 2%);
2. detector geometry (taken as 50%);
3. branching radio (69.4%);
4. different integration times (normalised to 5 minutes).

Results and discussions

Plots showing the activity as a function of angle were produced for many of the laser shots. Figure 4 is a good example, which shows an activity profile.

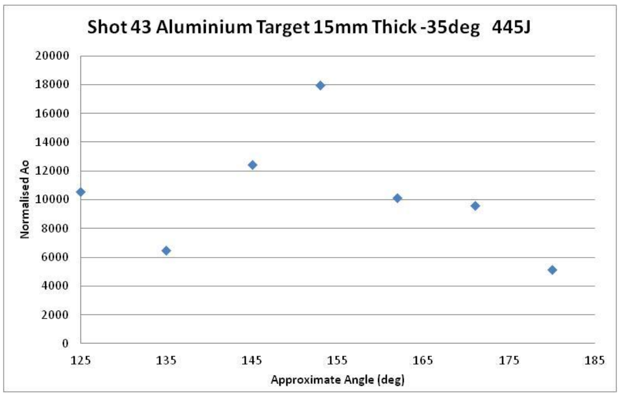

Figure 4: The activity as a function of angle (in degrees) around the laser target for shot 43.

For shots with copper blocks inside the laser chamber, 180 degrees is the approximate position of the laser axis.

Some laser shots clearly produced higher activation than others. It was desirable to quantify the effect of different variables to the activity, however, there are many to consider:

1. material of the laser target;
2. thickness of the laser target;
3. target angle w.r.t. incident laser beam;
4. laser energy (this is difficult to keep consistent between shots);
5. pre-pulse added (or not);
6. use of steering magnets (or not).

Due to the number of variables, and the number of laser shots, there is limited data to determine the repeatability of the measurements. That said, some findings of note include:

1. when the copper blocks were outside of the chamber, the activation is significantly lower;
2. the highest levels of activation were seen with thicknesses of 3mm of copper (including 4.5µm plastic-coated copper) (Figure 5);
3. 3mm tantalum also provided high activation but this was seen to be variable (Figure 6);
4. aluminium targets gave lower activation.

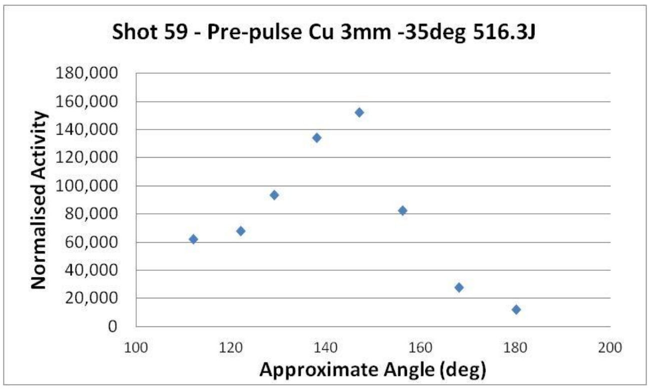

Figure 5: The result from a 3mm copper target.

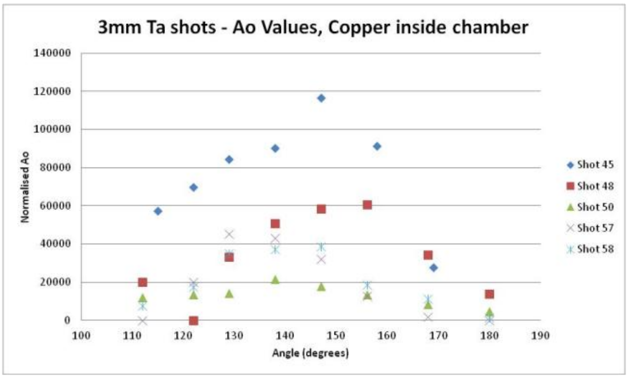

Figure 6: The combined results from shots on 3mm tantalum target.

The threshold energy to induce photonuclear activation in ^{63}Cu is given in reference 1 as 13MeV. The cross section (σ) of the reaction peaks at approximately 16MeV and stops at ~22MeV. Based on this, there must be a photon flux with energies between ~13-22MeV. The probability (P) of an interaction is given in Equation 1, where N_A is Avogadro's constant, ρ is the density, A is the area and m is the mass (in atomic mass units).

Taking the inverse of the probability and multiplying this by the activity (A_0) gives the flux.

Equation 1: $$P = \frac{N_A \rho \sigma}{Am}$$

When calculated, fluxes of the order of 10^6 photons were produced in some laser events. High fluxes were seen with the 3mm copper targets in shots 51 and 59 and the 3mm tantalum target in shot 45.

Conclusions

The ionising radiation from different laser targets was seen from the activation of copper blocks placed inside and outside of the chamber.

The fact that there is photonuclear activation of copper-63 means that photons with energies between approximately 13 and 24MeV were produced. The fluxes of these photons can reach the order of 10^6 photons.

Acknowledgements

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