NEUTRALIZATION OF EXPLOSIVE DEVICES WITH HIGH-POWER LASERS

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Abstract

The neutralization of improvised explosive devices (IEDs) in a civilian environment can pose a serious danger to clearing forces and the population. Therefore, the development of new neutralization techniques with improved safety is an ongoing field of research. One example of current research activities is the FP7 project ENCOUNTER, which aims at the development of innovative, novel neutralization techniques and the rating of their safety and reliability for the application in an urban environment in comparison to established, existing neutralization techniques.

In this paper, we introduce the FP7 project ENCOUNTER with a special focus on the neutralization of IEDs by high-power lasers. The working principle of laser neutralization is explained, and the setup of a laboratory test environment is presented that allows for a detailed study of the processes involved when IEDs are irradiated by a high-power laser. Examples of the observations that were obtained from generic IED models under laser irradiation are presented, and an outlook on further work is given.

Keywords: Laser, neutralization, safety, explosive, IED, disposal, detonation, deflagration, burning, X-ray, high speed diagnostics.

1 INTRODUCTION

The FP7 project ENCOUNTER ("Explosive Neutralisation and Mitigation Countermeasures for IEDs in Urban/Civil Environment") addresses the safe neutralization of improvised explosive devices (IEDs) in a civilian environment [1]. ENCOUNTER is a collaboration between the coordinator FOI (Sweden), Fraunhofer EMI (Germany), Blastech (UK), University of Sheffield (UK), Tamar (Israel), Isdefe (Spain), and the University of Freiburg (Germany). In addition, the consortium is supported by a thematic user group consisting of end users from different European countries. The ENCOUNTER project started in September 2012 and is planned for a duration of three years.

A central part of the project is the improvement of existing and the development of new neutralization techniques with the goal of increasing the safety of the population and clearing forces. This includes the neutralization of IEDs by clearing charges, high-power lasers, high-power microwaves, and barrel disruptors. These neutralization techniques are distinct in terms of the physical and chemical processes used for neutralization, stand-off capabilities, technical implementation and maturity level for application towards IED neutralization. In addition, the project includes the development of mitigation techniques and a risk analysis tool. The major elements of ENCOUNTER and their relation to each other, including the pursued neutralization and mitigation techniques as well as the risk analysis tool, are illustrated in Fig. 1.

In this paper, we are focusing on the neutralization mechanism of IEDs by high-power lasers. High-power lasers offer a high potential to increase the safety and flexibility of IED neutralization since they can be applied at large stand-off distances of more than 100 m. The application of high-power lasers for IED neutralization has already been demonstrated in a military context in the past. However, important safety aspects including the risk of high-order reactions, blast wave generation and fragment formation remain to be investigated for the safe application of this technology in an urban environment. Therefore, the setup of a laboratory test environment to investigate the time scales and processes involved in the neutralization of IEDs by laser irradiation is a central part of work in ENCOUNTER.

High-power lasers with an output power in the kilowatt range became commercially available with high compactness and efficiency in the recent years and are widely being used for industrial applications such as, e.g., cutting and welding. As an example, the single-mode fiber laser is characterized by high compactness, robustness, and efficiency in combination with an excellent beam quality and is therefore well-suited for the application in IED neutralization in mobile systems. Equipped with suitable optics, the laser beam can be focused over large distances of more than 100 m.

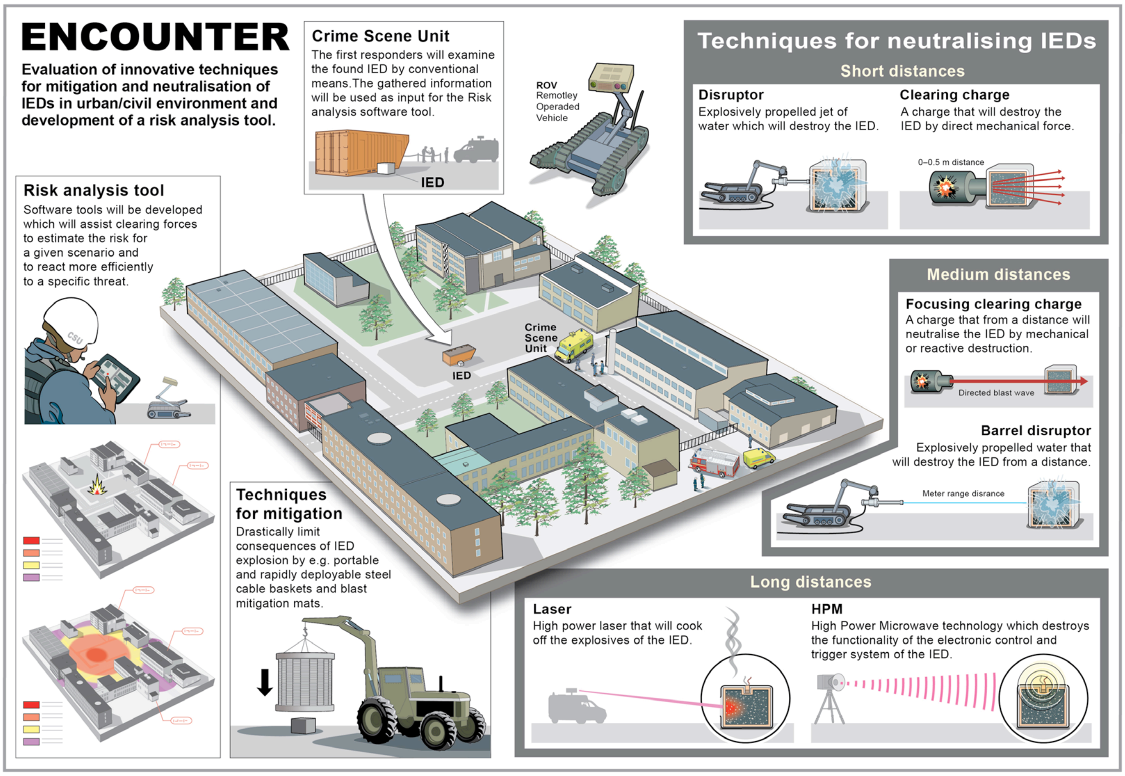

Figure 1: Image giving an overview of topics covered in the project ENCOUNTER. The project's objectives include the development and evaluation of various innovative mitigation and neutralization techniques for IEDs found in a civil environment. The project is funded by the Seventh Framework Programme of the European Commission.

2 WORKING PRINCIPLE OF LASER NEUTRALIZATION

For the application of a high-power laser for IED neutralization, different strategies are possible. If individual parts of the explosive device such as, e.g., power supply or release mechanism can be identified, they can potentially be disabled by intense laser irradiation. Here, we consider an approach which is based on the thermal initiation of a non-detonative reaction of the IED's explosive charge by intense laser irradiation. For an illustration of this process, Fig. 2 shows a high-speed video sequence from a laboratory experiment where an unconfined explosive sample was irradiated by a high-power laser. The laser irradiation leads to a temperature increase of the explosive material and finally to a low-order burning reaction of the sample.

For an application towards IED neutralization, it is important to mention that the reaction speed of the explosive material depends on several factors. The irradiation of unconfined explosives as shown in Fig. 2 typically does not result in a strong pressure increase, and consequently, a slow reaction burning of the explosive material is expected. In contrast, the detonation is a progress which takes place on a very short time scale and is accompanied by a strong, rapid pressure increase. The detonation is characterized by a thin reaction front that propagates through the explosive material at supersonic velocity. In addition, there are reactions on intermediate time scales like cook-off processes or deflagration. Cook-off is a generic term for processes in explosives that are heated by an external energy source [2]. Deflagration is a process where a reaction front propagates through the explosive material with a velocity below the speed of sound and is a typical result when cooking-off a confined explosive sample. An illustration of these reaction processes including a comparison of the different time- and pressure scales is shown in Fig. 3.

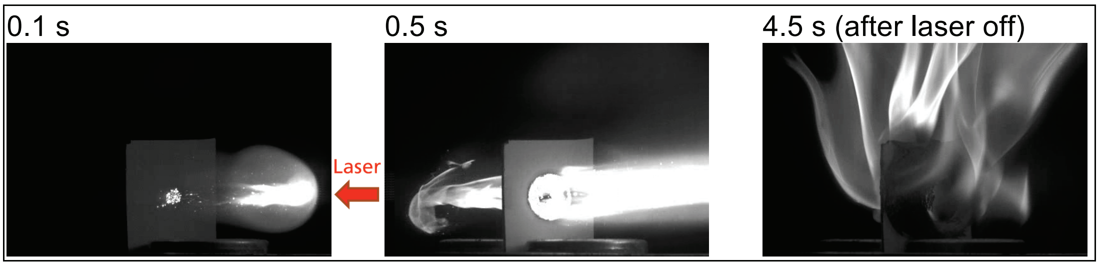

Figure. 2: High-speed video record of an unconfined explosive foil shows perforation as well as burning reaction during and after high-power laser irradiation.

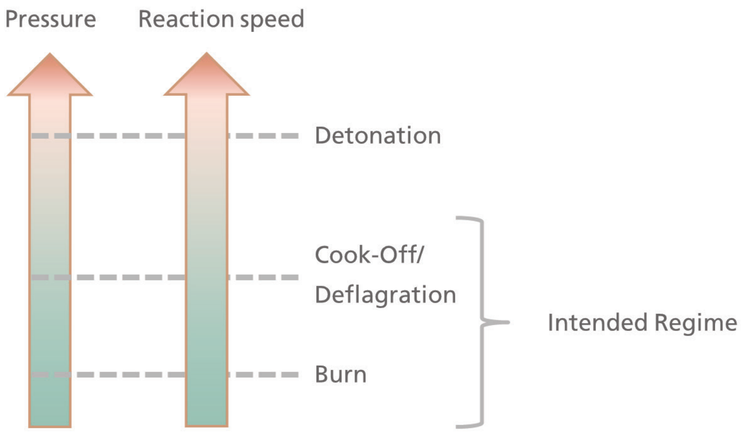

Figure 3: Scheme of reaction processes distinguished by increasing pressure and reaction speed. For IED neutralization with the high-power laser, a low-order reaction of the explosive charge is intended.

For the application towards IED neutralization, a low-order deflagration or burning reaction of the explosive material is intended in order to achieve a slow reaction with a small pressure buildup and thus to minimize the risk of damage in the IED's environment. In the ENCOUNTER project, important safety aspects including the risk of high-order reactions, blast wave generation and fragment formation have to be investigated for the safe and reliable application of this technology in an urban environment. For the systematic study of theses phenomena, a laboratory test environment has been set up and is described in the following chapter.

3 TEST ENVIRONMENT FOR LASER NEUTRALIZATION

For the experiments, a continuous-wave (cw) 10 kW Ytterbium multi-mode fiber laser at a wavelength of 1070 nm is available at Fraunhofer EMI. The installation of the laser in a ballistics laboratory allows the safe operation of the laser for the neutralization of explosive devices. The setup of the test environment is illustrated in Fig. 4. The beam path is as follows: The laser light is directed through an optical fiber that is connected to a collimator. The collimator produces a low-divergence laser beam with a diameter of about 24 mm. After leaving the collimator, the laser beam is transmitted through a fused silica window into a sealed tank and is directed onto the sample by a steering mirror. The sample is located in a bunker shown on the left side of Fig. 4. The steering mirror can be controlled electronically, allowing a precise alignment of the aiming point of the laser. The area behind the sample and the steering mirror is additionally protected by beam dumps.

For the investigation of the processes during irradiation of the sample, a broad spectrum of high-speed diagnostics is available at EMI. For the experiments shown here, a high-speed video camera in combination with a flash X-ray setup is used. The photograph in Fig. 5 shows the sample in the viewing direction of the high-speed video camera. The X-ray setup consists of two flash X-ray tubes and an X-ray film cassette located behind the sample. The geometry is chosen such that each X-ray tube produces an individual image on the X-ray film that is spatially well separated from the image produced by the other tube. While the X-ray setup allows the investigation of possible fragment formation, the high-speed video camera helps to interpret the X-ray images and reveals additional information regarding the behavior of the sample during laser irradiation and the time scales of the reaction of the explosive material.

4 EXAMPLES OF LABORATORY EXPERIMENTS

For the demonstration of the potential of the laboratory setup, first experiments with model IEDs were carried out. The model IEDs consisted of a cylindrical steel body that was filled with an explosive and sealed with end caps. The sample design is shown in the CAD drawing on the right side of Fig. 5. The sample was either irradiated axially on the cap or laterally on the mantle. In the following section, examples of experimental data obtained from samples filled with ANFO and Composition B are presented.

Fig. 6 shows a sequence of images from the high-speed video camera that was recorded during the irradiation of an ANFO filled sample. In the sequence, the formation of a hole in the mantle due to laser irradiation is observed, followed by a slow burning reaction of the ANFO filling. Burning of the explosive also leads to a throw-out of material in the perforated area. No fragments were generated in the case of the ANFO sample.

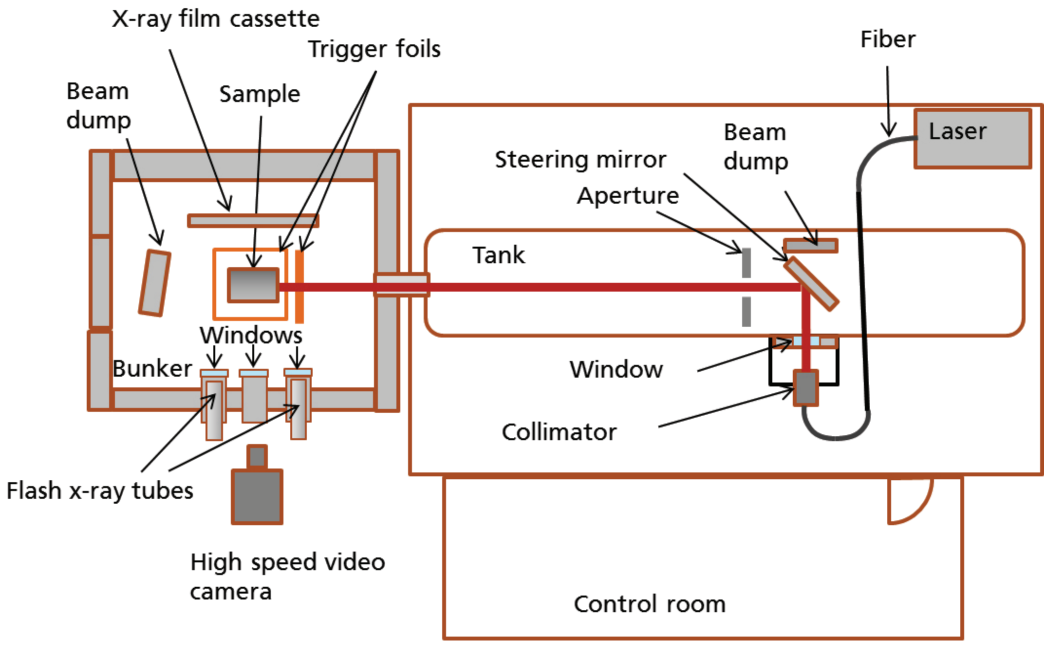

Figure 4: Schematic top view of test environment showing the laser as well as the beam path to the sample inside a reinforced chamber.

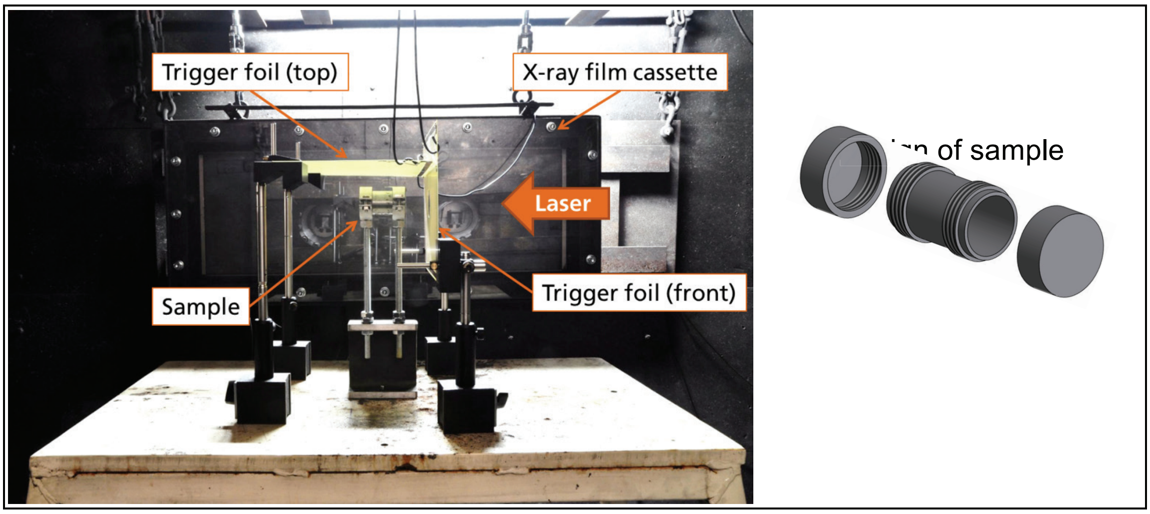

Figure 5: Left: Photographic side view of the sample from the perspective of the high-speed video camera. The laser is incident from the right side through a prepared hole in the frontal trigger foil. Right: Sample design for the test of the experimental setup.

A different behavior was observed for the samples filled with Composition B. In the example shown in the image sequence in Fig. 7, the reaction takes place on a shorter time scale, and the rupture of the shell occurs due to the pressure that is built up inside the sample and is accompanied by a bright flash and the formation of a small number of fragments. From the last frame in Fig. 7, it is evident that the reaction does not consume the entire explosive. Instead, two large fragments of unreacted Composition B can be identified between the sample and the frontal trigger foil. This leads to the assessment that the reaction was a deflagration.

Fig. 8 shows photographs of two samples filled with ANFO and Composition B, respectively, after laser irradiation. The high-speed videos and the condition of the shells after laser irradiation indicate that the reaction type was non-detonative in all preparatory tests.

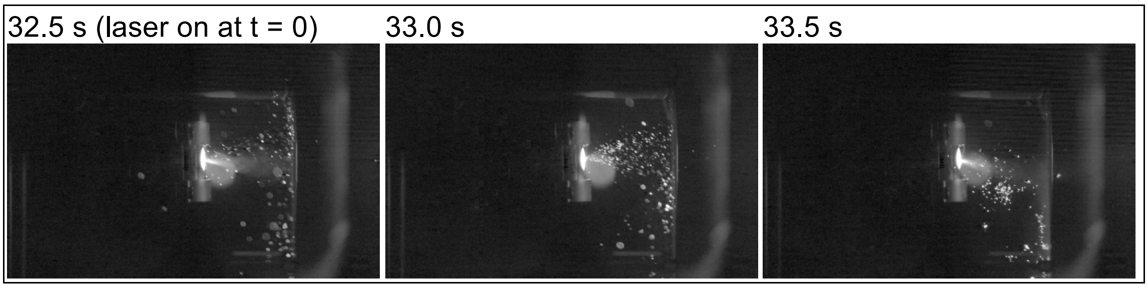

Figure 6: Sequence of images from a high-speed video showing the reaction of an ANFO filled sample irradiated with a laser power of 1 kW. The sequence shows the perforation of the mantle and burning of the explosive material without fragment formation.

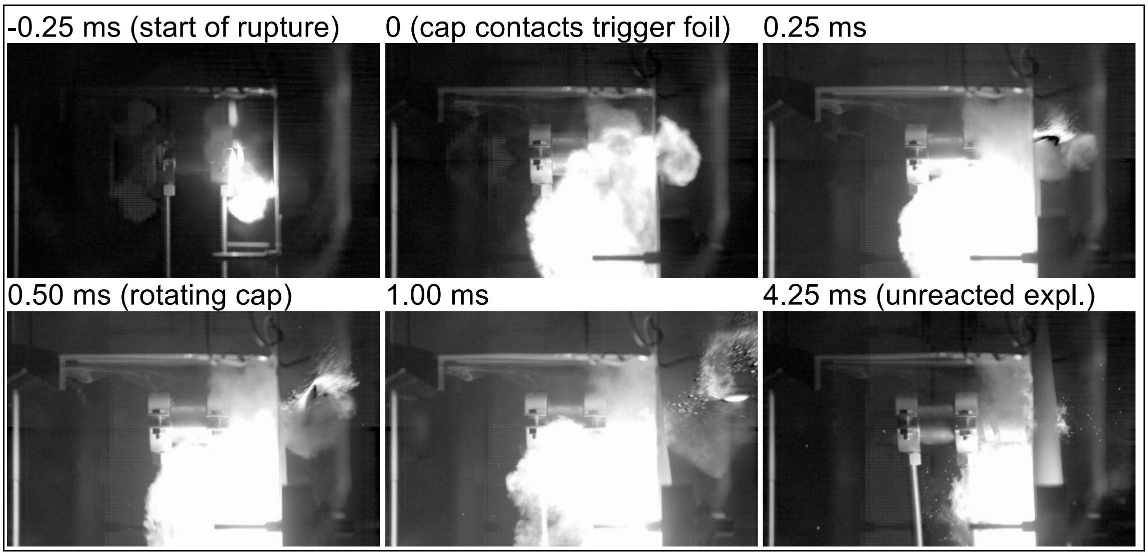

Figure 7: Sequence of images from a high-speed video showing the reaction of a Composition B filled sample irradiated with a laser power of 3 kW. The reaction takes place on a shorter time scale, but is still non-detonative. The sample fails at the laser irradiated cap on the right and a bright flash emerges.

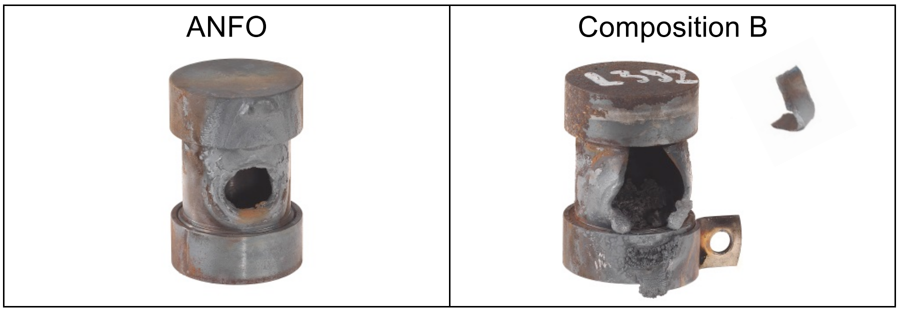

Figure 8: Photographs of ANFO and Composition B samples after lateral laser irradiation with laser power of 1 kW. The ANFO sample was perforated by the laser, whereas the mantle of the Composition B sample was ruptured by the pressure inside the sample. The explosive filling could be completely removed by the laser irradiation.

For a more quantitative analysis of the reaction strength in the Composition B samples, the fragment velocities were determined from the flash X-ray measurement. As an example, Fig. 9 shows two X-ray images that were obtained during laser irradiation of a Composition B sample with a delay of 100 µs. The positions of two fragments are clearly visible in each image, demonstrating that the X-ray setup is well-suited for this type of measurements, since the image quality is not affected by dust particles or by the bright flash originating from the reacting explosive. In the example shown, the measured velocity of the highlighted fragment is 196 m/s. For the interpretation of the experiments, the measured fragment velocities are compared to the Gurney velocity of Composition B of about 2 km/s which can be regarded as an expected fragment velocity in the case of a detonative reaction [3]. For all investigated samples, the observed fragment velocities were less than 10 % of the Gurney velocity which supports the interpretation of a non-detonative reaction in the laser irradiated IED models.

5 COMPUTER SIMULATIONS OF THERMAL EFFECTS

The experimental work is supported by numerical simulations that are intended for predicting the response of the explosive sample to high-power laser irradiation. The foundation was laid by simulating the transport of the laser-induced heat from the confinement into the explosive filling. An example of a simulated sequence of images showing the temperature distribution in a model IED irradiated with a laser power of 1 kW is displayed in Fig. 10. It is apparent that the heat conductivity of the explosive is several orders of magnitude lower compared to the steel shell and leads to a strong temperature gradient at the steel-explosive interface. In combination with experimental measurements of the temperature and pressure evolution inside the laser irradiated samples, important information of the time scales of the thermal processes and the reaction kinetics of the explosive material can be obtained [4].

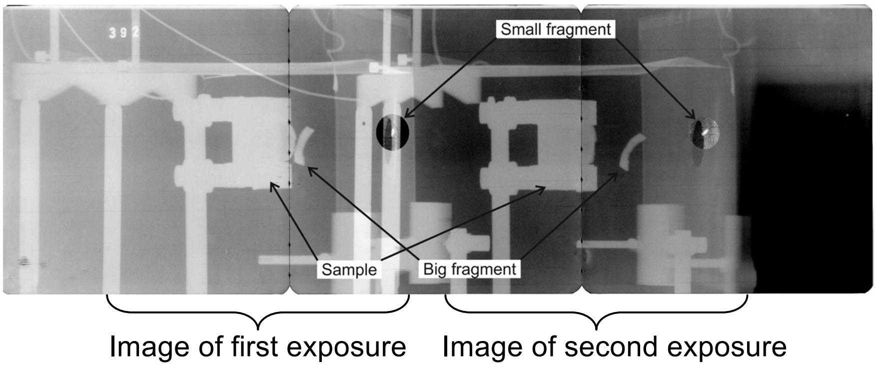

Figure 9: Double X-ray image of a laterally irradiated Composition B sample mounted on a vertical pillar. The image on the right side is generated with a predefined time delay of 100 µs with respect to the left image. The small fragment triggering the first flash X-ray tube is highlighted by a circle with enhanced contrast. In addition, the formation of a second fragment is visible on the images.

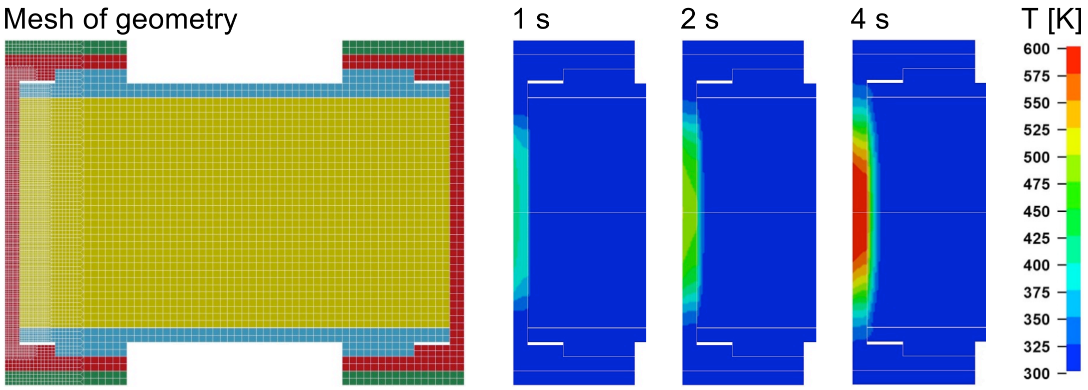

Figure 10: Mesh of sample design from Fig. 5 with additional mount (green) and simulation results showing the temperature distribution resulting from a 1 kW laser beam incident onto a Composition B sample from the left for different points of time. For a clear arrangement, only the left part of the sample including the left cap is shown.

6 SUMMARY AND OUTLOOK

A laboratory environment for systematic, quantitative studies of the neutralization of IEDs by irradiation with a high-power laser is presented. The laboratory is equipped with high-speed measuring technique including high-speed video cameras and flash X-ray imaging. For the demonstration of the potential of the laboratory setup, samples consisting of a cylindrical steel tubes filled with different explosive materials were irradiated with laser powers in the kilowatt range. It could be shown that the implemented diagnostics is well-suited for the characterization of the occurring phenomena during laser irradiation and for the investigation of important safety aspects. For all irradiated samples, a non-detonative reaction was observed, and the samples were in a safe state after a cooling phase.

The presented work is part of the FP7 project ENCOUNTER that started in September 2012 and is planned for a duration of three years until August 2015. In the next stage of the project, a test matrix will be defined and the developed neutralization techniques including the high-power laser will be evaluated in terms of safety and reliability for specific scenarios. On the basis of these investigations, it will be possible to give recommendations for the application of the novel neutralization techniques to end users.

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