LASERLAB-EUROPE

The Integrated Initiative of European Laser Research Infrastructures III

Grant Agreement number: 284464

WP33

European Research Objectives on Lasers for Industry, Technology and Energy (EURO-LITE)

Deliverable number 17

Experimental set-ups for Laser Induced Damage (LID) studies at low temperature

Lead Beneficiary:

GSI HELMHOLTZZENTRUM FUER SCHWERIONENFORSCHUNG GMBH

Due date: 31/10/2013

Date of delivery: 31/10/2013

Project webpage: www.laserlab-europe.eu

Deliverable Nature	
R = Report, P = Prototype, D = Demonstrator, O = Other	R
Dissemination Level	
PU = Public PP = Restricted to other programme participants (incl. the Commission Services) RE = Restricted to a group specified by the consortium (incl. the Commission Services) CO = Confidential, only for members of the consortium (incl. the Commission Services)	PP

A. Abstract / Executive Summary

Two experimental facilities were recently installed by the participants VULRC and GSI-HIJ as a prerequisite for the deliverables 33.16, 33.18 and 33.19. The equipment is designed to operate with various types of light sources, namely Ti:Sapphire, Yb:KGW, and Nd:YAG lasers, generating fs to ns pulses at fundamental wavelength and higher harmonics. Utilization of advanced laser parameter monitoring and clean room conditions ensures comparability of absolute threshold values. Reliable measurements in air, vacuum and cryogenic temperatures according to ISO 112541 standard provide the basis for comparable test results. Schematics and the efforts to set up the facilities are herewith reported. With the new facilities it is now possible to benchmark laser components exactly under the conditions they are intended to operate. Both installations cover the increasing demand from partner institutions for sample testing and thus open up possibilities of comparative and complementary studies.

B. Deliverable Report

1 Introduction

There are several major bottlenecks of modern high power diode pumped laser systems, mainly fluence in amplifiers and pulse compressors is limited by:

- the onset of laser-induced damage threshold as well as
- efficiency of removal of residual heat from the gain medium.

Cryogenic cooling is a means to improve laser efficiency at lower beam extraction fluences and at the same time it increases the thermal conductivity of the laser material. Accordingly, modern laser systems and their components are often operated in extreme environmental conditions such as vacuum and low temperatures. Similar conditions can be found in laser systems used for space applications. However, there is a lack of understanding how LIDT of the laser materials performs if they are operated under these conditions. For example, it is well known that for dielectric optical coatings LIDT changes when altering the environment from air to vacuum. This negative effect of vacuum was already mentioned in literature and especially a reduction of the UV laser damage threshold is known. The performance of coatings in vacuum is affected by the built-up of a contamination layer under high fluence irradiation at the presence of outgassing materials. However, similar ageing effects are not very well investigated especially at low temperatures, where condensation of materials on the cold surfaces is more likely. To open up new possibilities for studies of such kind flexible technical solutions are necessary to fulfill nowadays demands for damage testing in various environments. The exact measurement of LIDT is the fundamental work to benchmark materials, surface preparation, and coating techniques in order to develop optical elements with higher durability and reliability in high peak power laser systems.

These LIDT measurements require test benches that allow an exact simulation of the final operational conditions of the investigated samples and an exact monitoring of the applied laser pulse parameters. It was intended to prepare two of such test benches in Vilnius by participant VULRC and at the IOQ Jena by participant GSI-HIJ.

The installations at both participant sites, will allow comparative and complementary studies on a larger number of samples with a broad range of laser pulse durations and ambient conditions. This report summarizes the efforts made by VULRC and GSI-HIJ participant to accomplish this task.

2 Objectives

Within the scope of EURO-LITE project two laser-induced damage threshold testing facilities have to be installed by VULRC and GSI-HIJ that enable investigations of laser materials and other optical elements at relevant laser operation and ambient conditions following international standards [1]. These conditions include normal air pressure, vacuum, and cryogenic temperatures. The purpose of this deliverable is to report the development efforts and the status of the above mentioned technical solutions.

3 Work performed / results / description

3.1 The laser damage test facility at the IOQ Jena (GSI-HIJ)

In the frame work of the project the damage test facility at the IOQ Jena was completed. It allows to scan the sample in vacuum and cryogenically cooled with the focussed beam of a home made diode pumped ns-Yb:YAG laser system. Damage threshold is estimated by ex-situ inspection of the sample irradiated with pulses of varied energy. With this procedure a damage test following ISO norm 212541 [1] can be carried out. An overall scheme of the damage test setup is seen in Figure 1.

The laser consists of a Q-switched ns-oscillator and a multipass booster amplifier. The oscillator is equipped with a cavity as short as the necessary intra-cavity components namely the pockels cell, the laser head, and the thin film polarizer, that is used in reflection. The pockels cell is switched on and off to provide two polarization switching edges. By this means pulses as short as 3 ns are generated. Optionally, the oscillator can be used as a regenerative amplifier, if seeded by a wavelength in the amplification band of the Yb:YAG crystal. The laser crystal of the oscillator is pumped by a fiber coupled 940 nm laser diode with a maximum output power of 10 W. The repetition rate of the oscillator is variable in a wide range and typically set to 1kHz in order to provide maximum stability and pulse energy.

After the oscillator the laser beam is rotated in polarization by 45 degree and a polarizer is used to split the single pulse into two. These pulses are then recombined with another polarizer after a delay stage, what allow to freely adjust the delay between the pulses. An additional waveplate and polarizer behind the re-combiner brings the polarization of the two recombined pulses back to the same direction, whereas the waveplate allows to redirect the pulse energy to one pulse or the other with an arbitrary ratio (see Fig. 4). Because both pulses now travel collinearly with the same polarization through the amplifier to the damage test sample, it is guaranteed, that both pulses exhibit very similar properties.

Finally the pulses are amplified in multi-pass amplifier. The amplifier uses a relay imaging technique with a vacuum tube covering the focal plane in order to prevent arcing in air. In this amplifier the Yb:YAG crystal is pumped by a 2.5-kW-laser diode stack pulsed with 1 ms pulse width. A maximum energy of 200 mJ (in total of the two pulses) can be delivered. For the single pulse damage tests 100 mJ are typically used. This energy is variably attenuated in front of the focusing and scanning part with the help of a waveplate and a polarizer. The polarizer allows a polarization distinction ratio of better than 5000.

In order to move the focal spot to different positions on the damage test sample a two axis scanning stage is placed behind the 2 m focal length focusing lens. The scanning of the laser beam instead of moving the damage test sample allows placing the sample into a vacuum chamber with fixed position. The vacuum chamber is equipped with a turbo pump and a mass spectrometer as could be seen in Figure 2. If samples are measured at low temperature a pressure of 10^{-7} mbar is awaited before the cooling process is started. It was observed that a pressure better than 10^{-6} mbar is needed in order to avoid surface contamination by condensing substances. The vacuum tube in front of the sample and behind the sample is long enough to avoid nonlinear effects and damages of the windows by the focused laser beam. Therefore the total length of the chamber has to be at least 2 m. An image of the focused laser beam is shown in Figure 3.

Inside the vacuum chamber samples are placed in a copper holder with good thermal contact. The copper holder is attached to the cold finger of a closed loop cooling device that was provided by company Cryospectra (Austria). The cooler has a cooling power of up to 130 W at a temperature of 130 K. Additionally, the copper holder can be heated by a resistive heater to freely adjust the temperature between 130K and room temperature. The temperature is measured by a thermal resistor and controlled via the heater.

For every pulse used for damage testing pulse width, pulse energy, and far field beam profile as an image of the focal spot is monitored and used to determine the applied maximum energy density. All data are collected by a computer that also controls the two axis scanning stage of the laser beam. Additionally, two more camera images are taken from a green cw laser, that was focused by the same lens as the high energy pulse, and that is back reflected from the sample surface to the camera. One image is taken before and another one after the short pulse irradiation. These images allow an online diagnostic of a permanent surface degradation of the sample at the position of the laser focus. While this online diagnostic is sensitive to any cracks or deformations of the surface, it is not sensitive to subsurface damages or very small damage sites. That's why the full damage test procedure also includes an inspection of the sample with a microscope (Carl-Zeiss, Germany), that offers dark field and other contrast enhancement techniques to observe even smallest permanent degradations of the irradiated sample.

Figure 2 shows a picture of the vacuum system of the damage test facility at the IOQ Jena. On the right side the turbo pump and measurement equipment is placed. The ns diode pumped Yb:YAG-laser is on the left, outside the picture.

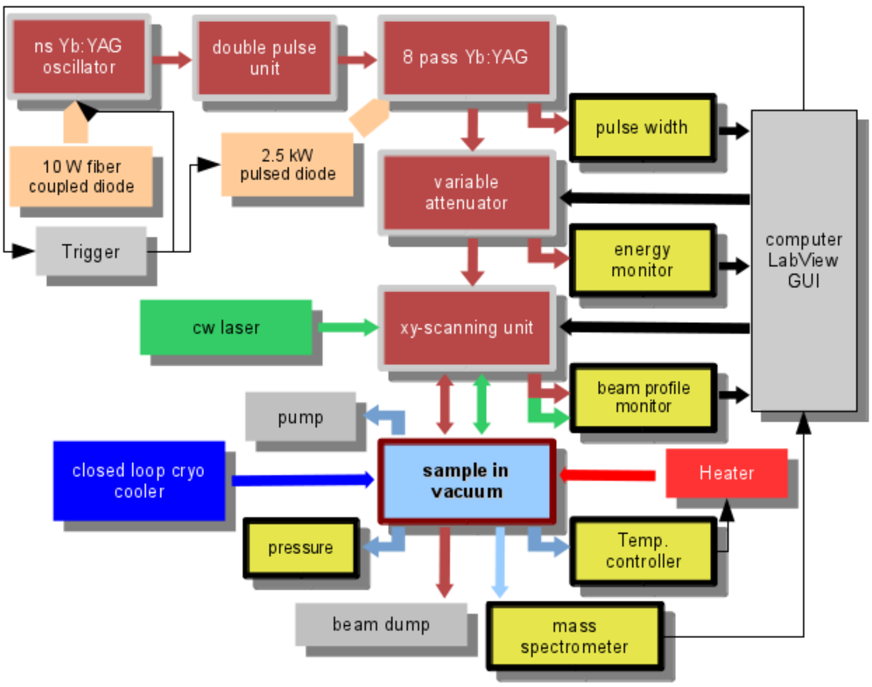


Figure 1: Scheme of the damage test setup.

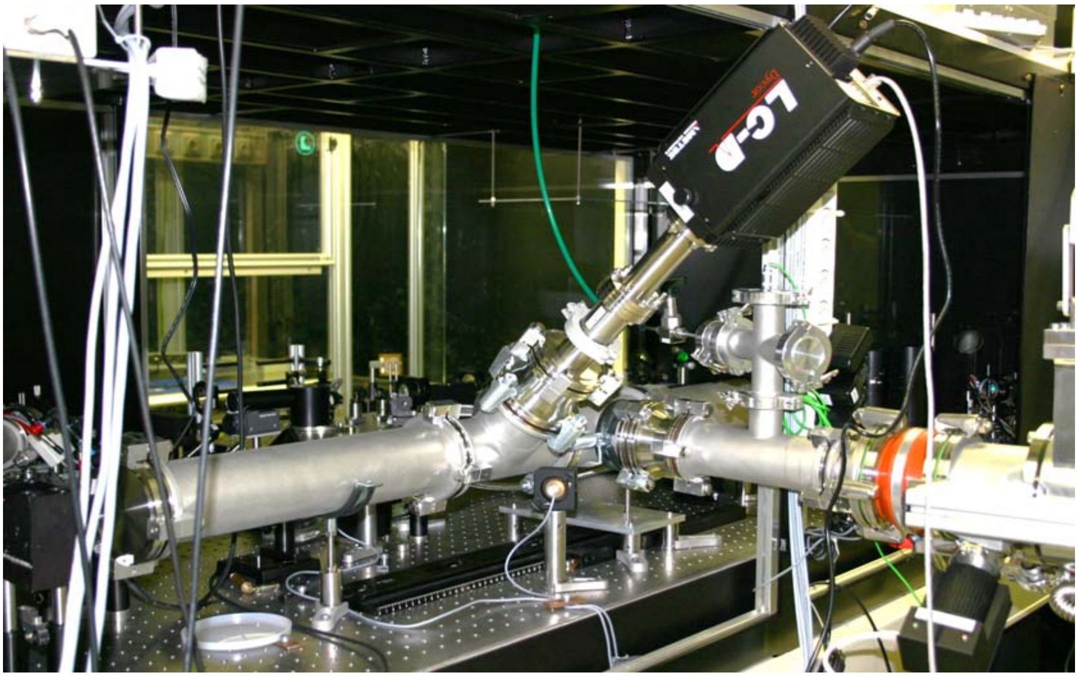


Figure 2: Vacuum chamber of the damage test facility at IOQ Jena with cooling finger, turbo pump, and mass spectrometer.

In figure 3 the far field image of the laser is displayed. Such an image is taken for every shot in order to ensure exact knowledge the intensity distribution at sample surface and to calculate the applied fluence. Together with the pulse width measurement the laser intensity can be calculated for every pulse.

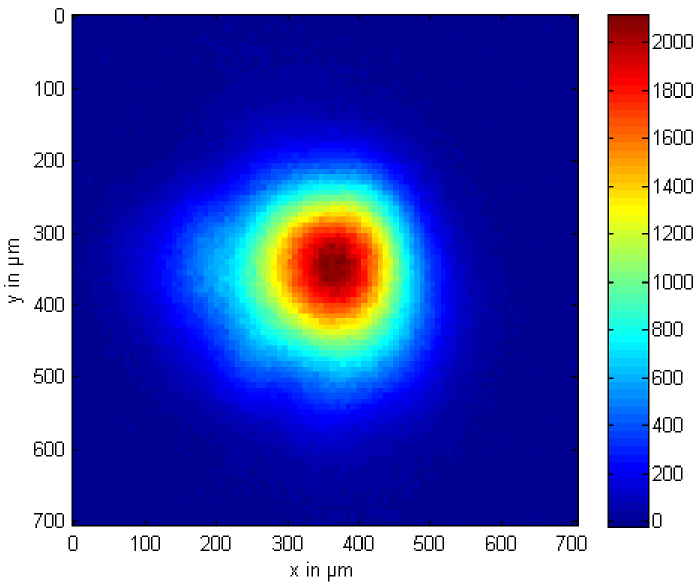


Figure 3: Beam profile of the damage test laser in the focal plane

In figure 4 an oscilloscope trace of the short pulse is shown were the double pulse generator is adjusted for two equal energy pulses with a delay of seven nanoseconds.

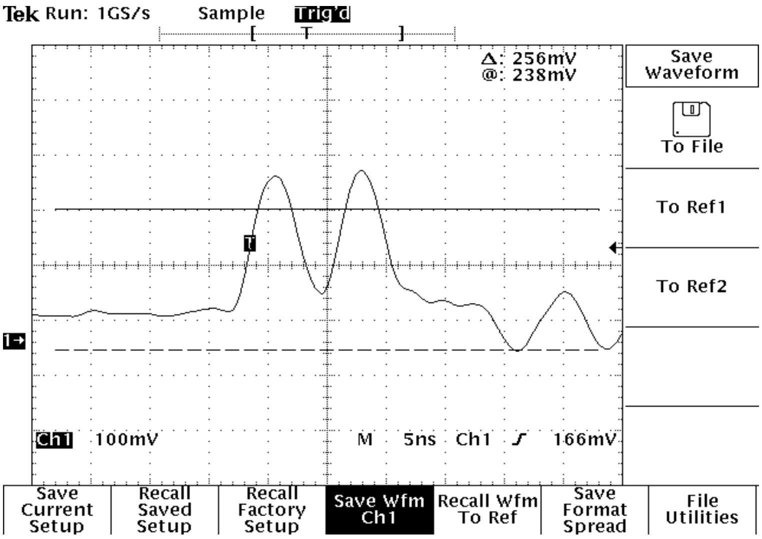


Figure 4: Double pulse structure of the laser. The oscillation on the right side are artifacts from cable reflections.

Figure 4 shows a microscope image from a damage test pattern of a coated laser material. In case of coated samples damages could be clearly identified. The corresponding plot of the damage probability versus fluence is depicted in figure 5. The linear fit is used to estimate the damage threshold as the interception of the curve with the horizontal axis.

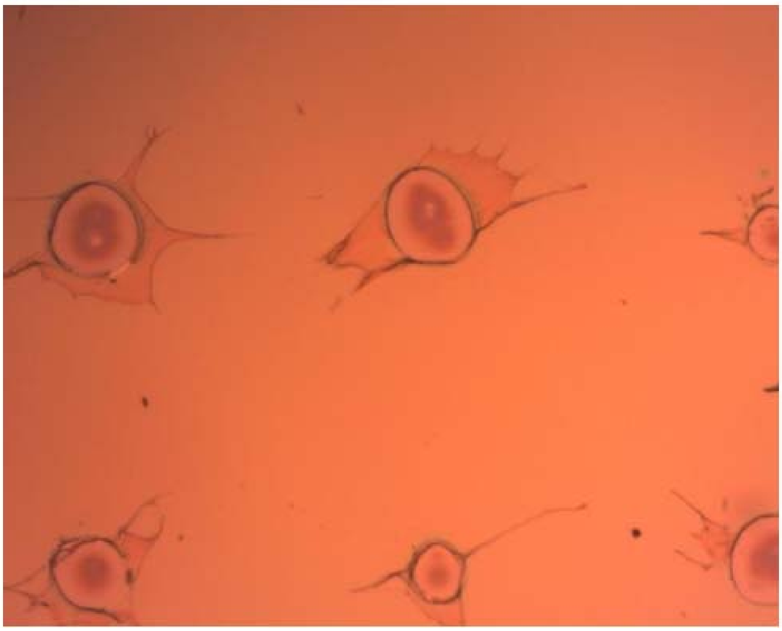


Figure 5: Typical microscope picture of the damage pattern on the surface of a sample (coated Yb:YAG ceramics at room temperature in this case).

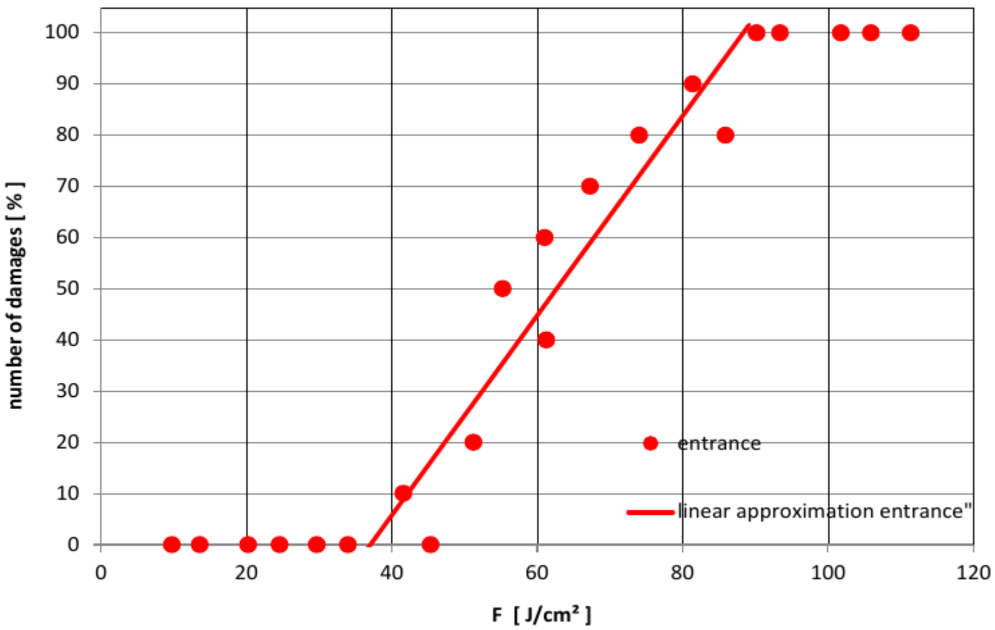


Figure 6: Damage probability versus fluence after evaluation of the damaged sites. The plot is used to estimate the laser induced damage threshold as the interception of the linear fit with the x-axis, what result in 37 J/cm2 in this example of an anti-reflection coated Yb:YAG ceramics. This measurement was made at room temperature.

3.2 The laser damage test facility at the Vilnius University (VULRC)

The sketch of LIDT test system developed at VU LRC is shown in Fig. 7. The apparatus consists of this key elements: high average power single longitudinal mode injection seeded Nd:YAG nanosecond laser source (connections to a Yb:KGW or a Ti:Sapphire laser are made and other lasers can be also used instead) wavelength conversion unit (frequency doubling and tripling via nonlinear crystals), calibrated high speed energy monitor combined with appropriate neutral density filter set, motorized attenuator (λ/2 plate combined with pair of polarizers), mechanical shutter, focusing optics, beam diagnostic unit (CCD camera combined with appropriate neutral density filter set), online damage detection unit based on photo diode and fast electronics and vacuum chamber combined with turbo pump system. The system is controlled via an attached computer together with the signal recording and controlling electronics. The measurement procedure is performed by an ”in house” developed computer program. The program controls all hardware devices and thus is able to realize various test procedures such as well-known 1-on-1, S-on-1, R-on-1 tests and the so called binary search technique (BST) routine. The angle of incidence can be varied in automated manner with a computer controlled rotation axis and an XY translation stage placed within the vacuum chamber.

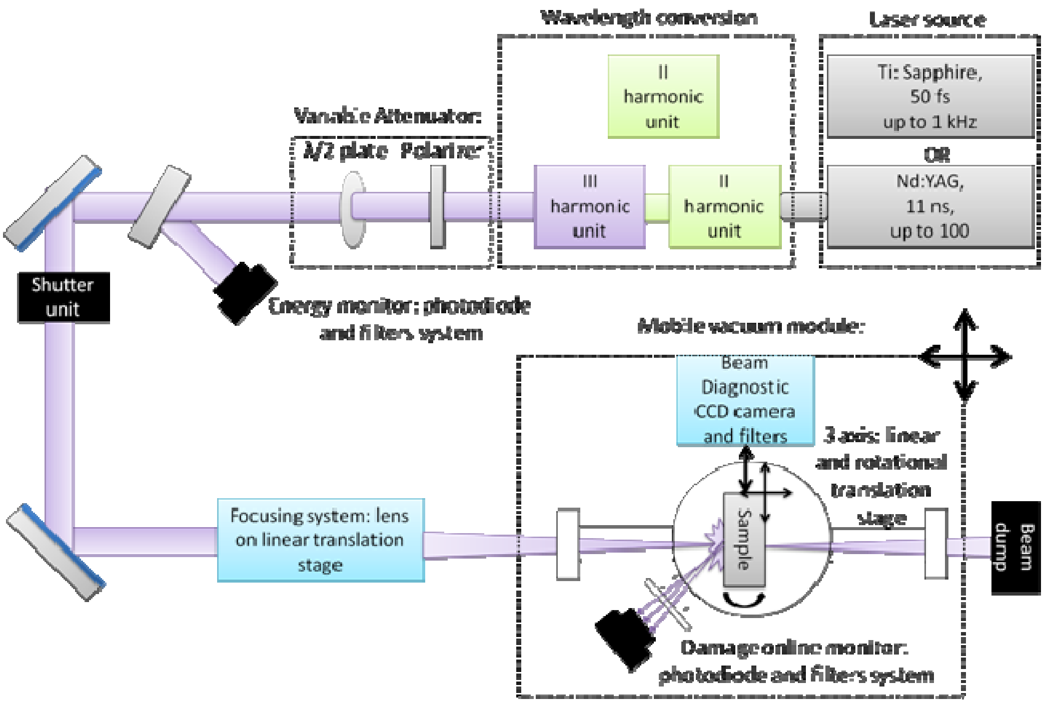


Fig. 7. Principal optical scheme realized at VU LTC

In order to conduct vacuum measurements with different laser sources often located at different laboratories a vacuum part shown in Figure 8 was developed as a separate (mobile) attachment. This module has its own vacuum translation and rotation stages and can be connected to an external cooling unit.

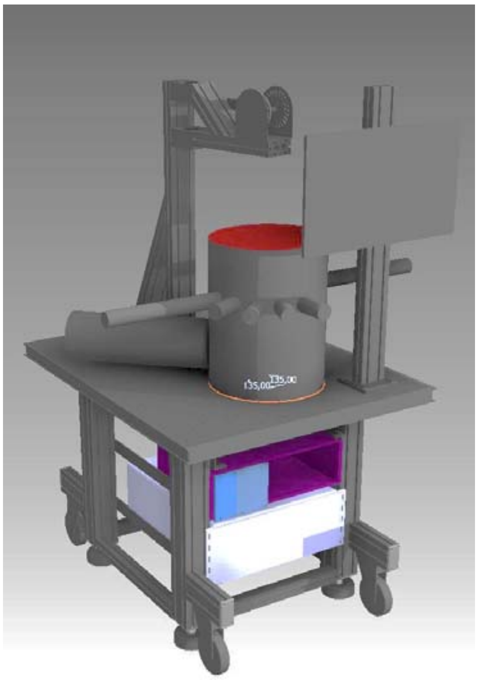


Fig. 8. Sketch of designed mobile vacuum system that can be moved to different laser sources located at different laboratories.

Laser induced damage testing is performed in a vacuum chamber assembled from commercial UHV-components. Basically, it consists of a large cylinder with multiple flanges and features sufficient ports for observation windows, sensors, analyzers and electrical connections. Irradiation is guided to the vacuum chamber through the fused silica optical windows. Two extension tubes are added at the entrance and exit ports of the system in order to extend the distance and decrease the probability of entrance or exit window damage. Test samples are placed in a six seat mount with good thermal contact. The mount is connected to the 3 axis translation stage (2 linear and 1 rotational axes) and can be thermally isolated from motors thus attaching the cold finger via flexible cooper braids.

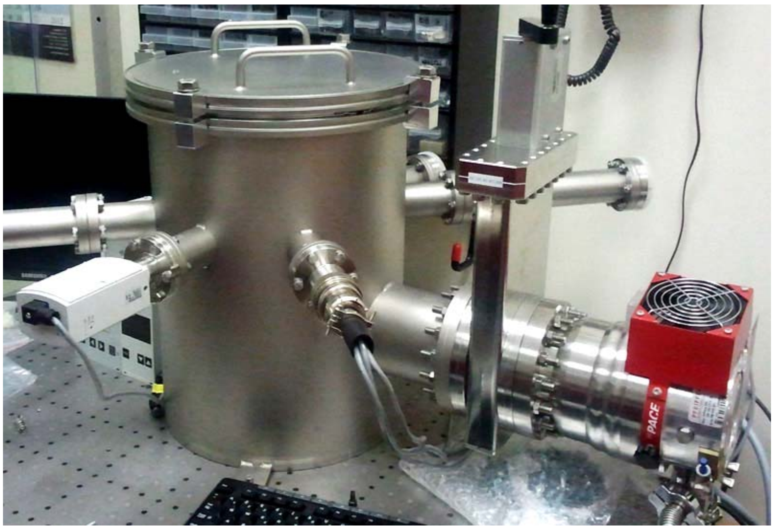


Fig. 9. Vacuum chaber for damage testing developed at VU LRC.

Vacuum within the chamber is created and maintained using two stage pumping system consisting of oil free pre-pump and secondary turbo molecular pump (Pfeiffer vacuum, HiPace 300) [Fig. 9]. Turbo molecular pump is attached directly to the chamber. Turbo-pump is connected to the vacuum chamber via manually controlled valve. Manipulating both pumps vacuum range between 10^{-2} mbar to less than $5.5x10^{-9}$ mBar could be achieved (in a clean chamber). Pressure in the chamber could be controlled via software by varying the varying speed of the turbo molecular pump from 200 Hz up to 1000 Hz. Vacuum is monitor by the pressure sensor (Pirani/Penning gauge).

A closed cycle, single-stage refrigerator system M350 CTI-Cryogenics (Fig. 10) was adapted for sample cooling. The typical cooling power of refrigerator system is shown in Fig. 11. The sample holder is attached to the cold finger via cooper braids. Additionally, the sample holder can be heated by a resistive heater to freely adjust the temperature. The temperature is measured by a thermal resistor and controlled via the heater.

A four-input, four-control loop cryogenic temperature controller 24C from Cryocon (Fig. 12) is selected for temperature control. Each input is independent and capable of temperature measurement to <200mK with an appropriate temperature sensor. The four-output control loop circuits feature a primary 50W heater, a secondary heater of 25W and two 10-Volt non-powered outputs. All control modes are supported by all outputs. The 24C front panel incorporates a large high resolution graphics TFT type Liquid Crystal Display.

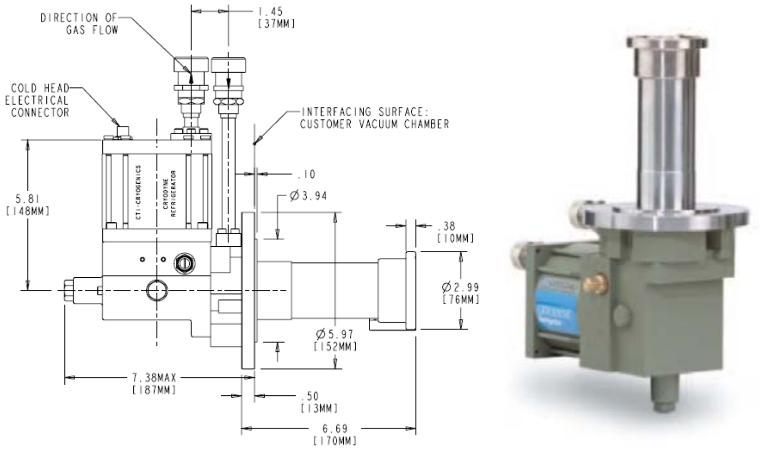


Fig. 10. Single stage M350 cold finger from CTI-Cryogenics

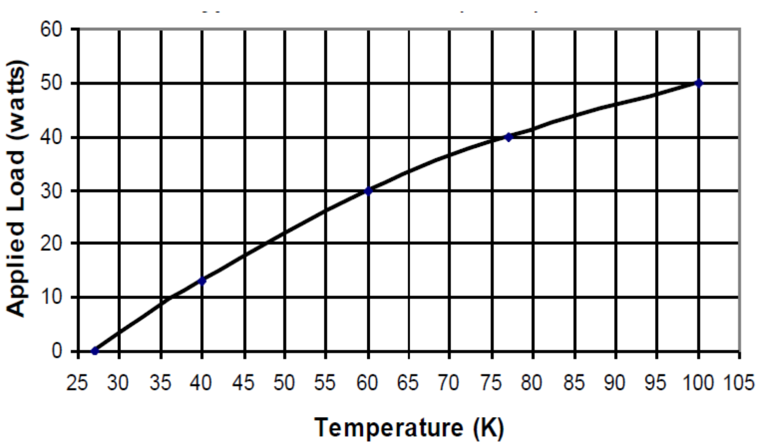


Fig. 11. Typical cooling performance of Cryodyne M350 refrigerator.

Fig. 12. Temperature control unit (Model 24C, Cryocon)

For laser exposure at cryogenic conditions three commercial laser sources - Yb:KGW (Pharos, Light Conversion) Ti:Sapphire (Libra, Coherent) and Nd:YAG (Hybrid, Innolas) are available at VU LRC. The capabilities of available wavelengths and pulse durations are summarized in Table 1.

Table 1. Available testing conditions at VULRC.

Laser type	Eff. pulse duration (FWHM, @ fundamental)	Standard* wavelengths, nm	Rep. rate, Hz	Polarization state
Nd:YAG (multimode) **Nd:YAG (SLM)**	3.5 ns 8-11 ns	1064	1-10 1-50	linear (S,P)
		532		
		355		
		266		
		213		
Yb:KGW	300-4700 fs	1030	1-50000 typical (up to 200000)	linear (S,P)
		515		
		343		
		258		
Ti:Sapphire	50-200 fs	800	1-50 typical (up to 1000)	linear (S,P)
		400		

A characterization of both temporal and spatial parameters of the Ti:Sapphire, the Yb:KGW, and the Nd:YAG laser was performed and summarized in Tables 1 and 2.

Table 2. Typical measurements of temporal laser pulse profiles at fundamental wavelength.

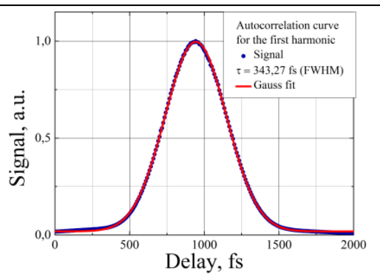
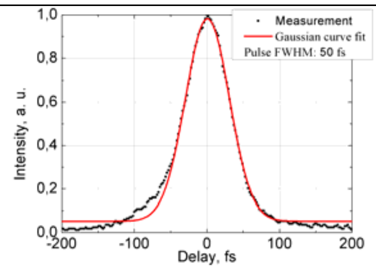
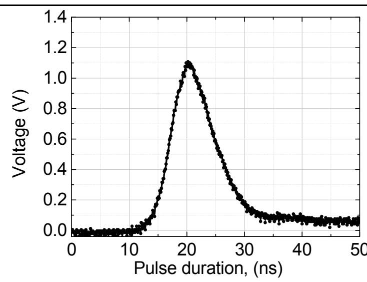
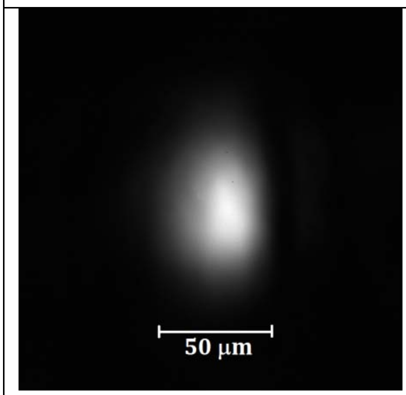
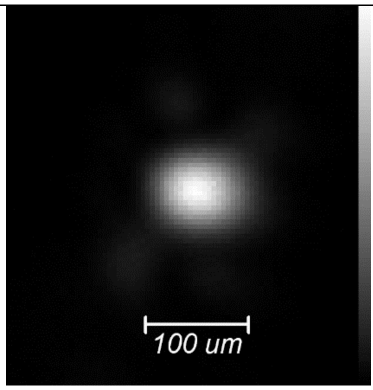
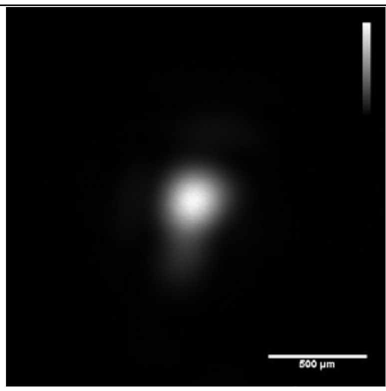
Yb:KGW (Pharos, Light Conversion)	Ti:Sapphire (Libra, Coherent)	Nd:YAG (Hybrid, Innolas)
		

Table 3. Typical measurements of spatial laser pulse profiles at fundamental wavelength.

Yb:KGW (Pharos, Light Conversion)	Ti:Sapphire (Libra, Coherent)	Nd:YAG (Hybrid, Innolas)
		

4 Conclusions

Two experimental systems are developed at VULRC and GSI-HIJ that are ready to fulfill the deliverables 33.16, 33.18 and 33.19. For measurement results see reports on these deliverables. By the participant GSI-HIJ a damage test facility was installed for laser induced damage testing under normal air pressure and vacuum conditions. Additionally a cryo-loop allows cooling the samples to temperatures in the range of 130 K to 300 K. The used laser system actually allows 3 ns pulses to be applied to the sample. An extension to other pulse width can be added on demand. Adjustable double pulses can be used too.

The installed equipment at VULRC is designed with mobile vacuum part and is thus able to operate with various types of light sources, namely a Ti:Sapphire, an Yb:KGW, and a Nd:YAG laser, generating fs to ns pulses at fundamental wavelength and higher harmonics at very broad range of repetition rates. The system is very flexible in realization of different measurement protocols such as well-known 1-on-1, S-on-1, R-on-1 tests as well as the so called binary search technique (BST).

A precise monitoring of all relevant laser parameters offers a highly accurate measurements according to ISO 212541 norm at both facilities [1].

5 References/Publications

[1] "Determination of laser-*damage* threshold of optical surfaces. Part 1: 1-on-1 *test*," EN-*ISO* Standard 2*12541* (International Organization for Standardization, 2011)