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TJNAF free electron laser damage studies

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Abstract

Laser material damage experiments were conducted at the Thomas Jefferson National Accelerator Facility (TJNAF) free electron laser (FEL) user laboratory with an average power of 100 W and a power density of $10^4\,\mathrm{W/cm^2}$. The FEL beam bombards the target with a steady stream of tens of millions of pulses per second each containing 50 MW of power in a short burst of ~ 1 ps. No conventional laser combines these characteristics, and no experiments have previously been done to explore the effects of the FEL pulse. The goal is to develop scaling laws to accurately describe large-scale damage from a MW FEL using small-scale experiments. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Laser damage experiments conducted at the Thomas Jefferson National Accelerator Facility (TJNAF) are the first experimental tests that study the damage from a short-pulsed laser at a high repetition rate with a few hundred Watts of average power. Scaling rules can be developed that will allow these small-scale damage experiments to represent the damage from a large, MW-scale laser.

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2. TJNAF FEL design and parameters

TJNAF free electron laser (FEL) is the most powerful FEL ever operated. The parameters of the TJNAF FEL are $\bar{P} = 1.7$ kW, $\bar{I} = 5$ mA, $\gamma mc^2 = 48$ MeV, $\hat{I} = 60$ A, $r_b = 100\,\mu$m, $\tau = 0.4$ ps, PRF = 18.7/37.4/74.85 MHz and $\lambda = 3$–$6\,\mu$m [1]. The requirements for a MW laser are $\bar{I} =$ 900 mA, $\gamma mc^2 = 100$ MeV, $I_e/c = 1800$ pC, $\hat{I} = 600$ A, $r_b = 300\,\mu$m, $\tau = 3$ ps, PRF = 500 MHz, and $\lambda = 1\,\mu$m [2]. The significant differences are increases in the peak current by a factor of 10, the repetition rate by a factor of 7, the electron beam energy by a factor of 2, and the pulse length by a factor of 7.

In July 1999, the laser operated continuously at 1.7 kW average power. Since there is no MW-class FEL to perform full-scale experiments, scaling is

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the only way to determine the effectiveness of a high-power laser. Scaling laws would allow predictions of large area damage from small area experiments. To achieve a power density of $10\,kW/cm^2$ [3], the 100 W FEL at TJNAF must use a spot size of $1\,mm^2$, while a 1 kW laser uses a spot size of $10\,mm^2$.

Scaling of the laser damage will only work, if the heat diffusion is independent of spot size. The characteristic thermal diffusion length represents the distance required for the temperature to drop to $1/e$ times its central value. So, the laser spot size must be much larger than the thermal diffusion length. Then heat will not diffuse outside of the laser spot and the spot will be heated effectively [4].

The pulse train of an FEL is different from other lasers and its interaction with matter at high average power has not been studied. FELs produce short, powerful pulses with a rapid repetition rate. The TJNAF FEL has a pulse length of $\tau = 0.4\,ps$ and a repetition period of $T = 27\,ns$. The peak power in each micropulse is 110 MW.

Comparing the TJNAF FEL to another short pulse laser is instructive. The Lawrence Livermore National Labs (LLNL) 1.053-μm Ti : sapphire CPA system [5] has a pulse length $\tau = 0.4\,ps$, but a pulse repetition rate of only 10 Hz, so the peak power is 25 TW, and the average power is 10 W. Note that the LLNL laser has a much higher peak power than the TJNAF FEL, but the TJNAF FEL has more than one hundred times the average power because of its high duty cycle.

3. FEL experiments

Samples of various materials were irradiated by a laser beam of wavelength $\lambda = 4.825\,\mu m$ through a calcium fluoride lens with a focal length of 300 mm. Two pulse repetition frequencies (PRF) were used; 74.85 MHz for the phenolic resin sample and 37.425 MHz for all other samples. The average power is 100–103 W. Since a lens focused the beam, the beam area decreased with distance along the direction of propagation to a minimum waist radius of 80 μm at the focal point [6].

An irradiance of $10\,kW/cm^2$ occurs when the sample is placed 26 mm in front of the focus. As the laser burns into a sample, the intensity actually changes about 10% due to diffraction.

One of the targets irradiated was Slip-cast Fused Silica (SiO_2). A calculation of the thermal diffusion length associated with heating the sample to its melting temperature was performed with a result of $D = 0.02\,mm$. Therefore, there is no significant thermal diffusion from the $1\,mm^2$ beam used at TJNAF.

One of the runs using silica punched completely through the material. A digital picture of run two was taken through an optical microscope as shown in Fig. 1.

Although the beam diameter was only 1.1 mm, the melted portion at the surface of the sample measured 5 mm in diameter. The hole is tapered with the melted portion on the back of the sample measuring only 2 mm in diameter.

Examination of the hole from this run through an optical microscope reveals a 1-mm thick layer of melted, and rehardened, SiO_2 filling the hole at the back of the sample. It was clear from the video and the rear power meter that burn-through occurred in run two, but melted material solidified and sealed the hole at the back of the sample. A picture of the back of the target taken through a scanning electron microscope (SEM), that shows

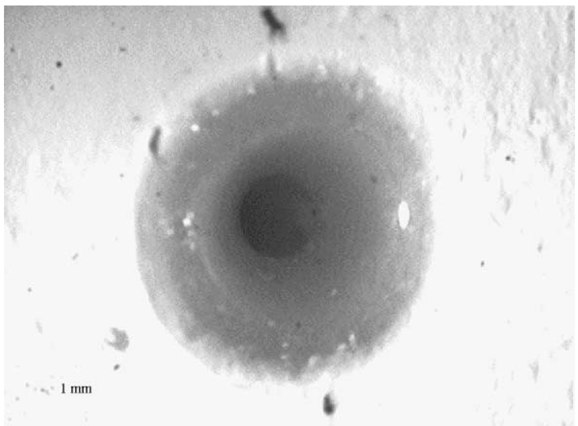

Fig. 1. Close-up of damage to slip-cast fused silica in run 2.

the hole from run seven is fairly irregular with a great deal of debris.

The volume of the hole in run two is estimated at 5.6 mm^3. The volume of the entire damaged region, including the melted and rehardened portion, is estimated to be 92 mm^3. Based on the density of fused silica, $\rho = 2.2\,g/cm^2$, the amount of material removed was 0.012 g, and the amount of material damaged was 0.20 g. The heat energy deposited during run two is 9.7 kJ deposited the 110 second run. The heat of ablation is then 48 kJ/g.

Another material, polyimide fiberglass, measured 11.4 cm × 10.1 cm and 2 mm thick. The damaged area of the sample, after irradiation, is shown in Fig. 2. The sample was irradiated three times from left to right with the sample 26 mm in front of the focus of the beam. Only the first run achieved burn-through of the material, with the entry hole 3 mm in diameter and the exit hole 1.5 mm in diameter. All three holes show significant charring, which adds an additional term to the heat transport equation and impedes ablation. Investigation with an optical microscope reveals a raised lip of material around the face of the hole that does not appear on the fused silica sample and much more roughness. The charred region extends to a diameter of 8 mm for run one, 6.5 mm for run two, and 5.4 mm for run three. The lip height is 0.3 mm for run one, 0.1 mm for run two, and 0.05 mm for run three. These measurements indicate that as the dwell time increases, the radial extent of the damage area increases, and more material is deposited around the edge of the hole. There is no evidence of melted and rehardened material present in the holes as found with the fused silica indicating a different mechanism for ablation in the two samples.

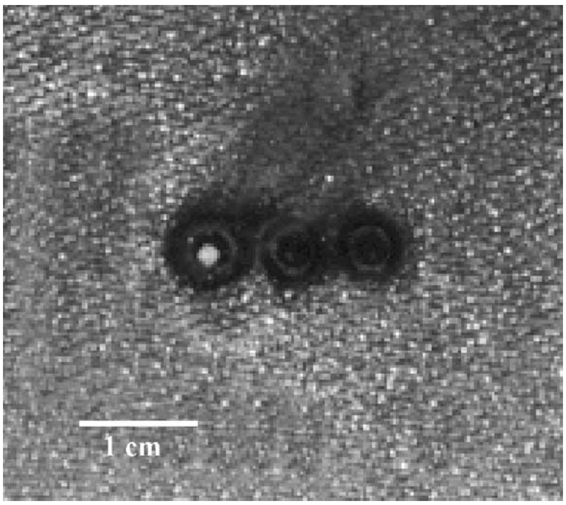

Fig. 2. Polyimide fiberglass target.

An F2 Epoxy sample measured 10 cm × 11.5 cm and 1.5-mm thick including a 1.6-cm thick polyurethane foam backing. The sample was irradiated three times and, in each case, it appears that the F2 Epoxy was completely penetrated and the ablation of the foam backing had begun, but not completed. The videotape showed flames engulfing the upper portion of the sample and the black charred area extending to the edge of the sample. Significant charring was evident when the sample was viewed with the optical microscope, similar to the polyimide sample. There was also evidence of some melting, but not as much as occurred in the fused silica sample. The holes appear to be filled with the charred debris of the polyurethane backing, making hole depth measurements difficult and rendering penetration depth rates unreliable.

The damaged region extends to a diameter of 11.3 mm for run one, 7.5 mm for run two, and 5.2 mm for run three. There is a lip around each of the holes, but much smaller than the polyimide sample showed. The lip for run one was 0.05 mm and for runs two and three the lip was too small to measure with the optical microscope mechanism. These measurements indicate that as dwell time increases the radial extent of the damage area increases, and more material is deposited around the edge of the hole. When wind is added to the test, debris may be removed from the hole during irradiation.

Two phenolic samples were tested. Phenolic sample 1 is circular with a diameter of 32.5 mm. There is a 7.1 mm hole in the middle of it. It varies in depth from 1.6 mm to 3.2 mm. Sample 1 was irradiated three times with the sample rotated 90° counterclockwise after each run. Run number one did not achieve burn through because of operator intervention. After initial irradiation, the rear camera showed that the sample had ignited. The FEL operators quickly stopped the experiment only to find that the sample had slightly charred on the reverse side and not burned through.

For run numbers two and three, the samples were irradiated for a full 10 s. Though not documented, burn through times for each run were different. Run number two is similar to run number three. The crater is not perfectly cylindrical, since the back face has a slightly smaller area than the front. There is a crater lip that is built up from the damage, approximately 1 mm high. Also, a white crust is present, probably from the separation of the resin into its elements during heating. The white crusts and lips are also evident on the back side for runs two and three.

Phenolic sample 2 is circular with a diameter of 31 mm. There is a 7.1 mm hole in the middle of it. It varies in depth from 1.5 to 3.8 mm. Sample 2 was irradiated seven times and rotated counter-clockwise after each.

All runs produced a lip around the entrance of the cavities ranging from 0.1 to 1 mm high. They also produced a white crust that must be some sort of elemental extract of the resin, probably separated during heating. Runs that did not burn through, one and four, created a crater shaped like an inverted cone with a rounded apex, probably due to the Gaussian nature of the FEL's laser beam. Inspection of the back side of run four, showed charring, a sign that the beam almost burned through. Runs that achieved burn through had a cylindrical crater, with the back edge slightly smaller than the front. Lips formed on the reverse side of the sample, just like the front side with the white crust around it.

Run number three is indicative of the runs with irradiances of 12 kW/cm^2, runs one through four. Run six is indicative of the damage produced by the runs with irradiances of 680 kW/cm^2, the other run was number five. Due to the high irradiance, the crater is smaller by a factor of two or three. The beams with more power density were able to punch through the material faster producing a much smaller lip as well. Note the existence of the same white crust but in lesser amounts.

Specific burn-through times were not noted for runs two, three, five and six. Future experiments should measure burn through times more accurately. The recession rate decreases nonlinearly as the exposure time increases. This decline in recession rate could be due to smoke and debris flying out of the crater while the beam is burning through the phenolic material. The smoke and debris impede the laser from doing damage. TJNAF is planning future experiments with wind, which might alleviate this problem.

Two pyroceram samples were irradiated at TJNAF in user laboratory number one. The first sample irradiated is pyroceram sample 1 and the other pyroceram sample 2. Pyroceram sample 1 is an irregular shape with an average depth of 1.4 mm. Fig. 3 is a picture of sample after 3 irradiations numbered from left to right. Pyroceram sample 2 is an irregular shape with an average depth of 1.4 mm.

4. Conclusions

This paper describes the first measurements of laser damage from the newly developed TJNAF FEL and the results could provide the basis for new directions for directed energy research.

The TJNAF FEL, which is capable of several hundred Watts of continuous average power, was used to simulate the damage from a MW-class laser by focusing the beam to a smaller spot size. The eventual goal is to develop

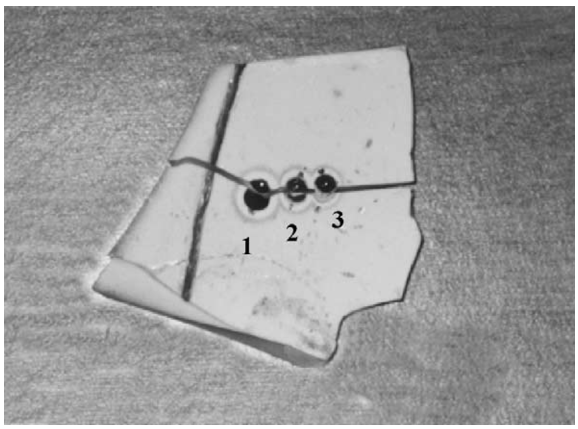

Fig. 3. Pyroceram target.

scaling rules that will reliably predict the damage of a large laser without having to bare the enormous cost of building the large laser first. The experimental data shows that the scaling concept with thermal diffusion calculations is promising. More detailed experiments varying wavelength, power, and spot size may be able to produce scaling laws, which would be invaluable, for future designers.

The extremely short sub-picosecond pulse length of the FEL beam is a result of the electron bunches. The TJNAF FEL has a unique pulse format with a rapid sequence of short, powerful pulses. The peak power in each pulse is about 100 MW lasting for only about one-half picosecond coming at a rate of 37/74 MHz. Other studies have shown that such short pulses may give as much as a factor of ten advantage in reduced fluence required to produce damage [7]. The experiments conducted for this paper began to collect data to show whether this advantage exists, but further experimentation will be required.

The TJNAF FEL is scheduled for an upgrade to 20 kW of power that will allow more flexibility in scaling experiments and further tests of scaling itself. Additional plans are for experiments, which include wind passing over the samples, weighing of the samples before, and after each run, new wavelengths, changing wavelength during irradiation, new pulse formats, and other sample materials. As experimental procedures are refined and the amount of data increases, more thorough analysis of the FEL beam and comparison to other lasers will become possible.

Acknowledgements

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