Utilizing ablation of solids for characterization of the focused beam of soft X-ray free-electron laser

J. Chalupsky[1,2], L. Juha[1], J. Kuba[2,3], R. Sobierajski[4], J. Krzywinski[4], J. Cihelka[1,5], V. Hajkova[1], S. Koptyaev[1], A. Velyhan[1], J. Krasa[1], M. Bergh[7], R. Bionta[6], H. Chapman[6], J. Hajdu[7], S. Hau-Riege[6], M. Jurek[4], C. Caleman[7], R. London[6], A. Krenz[8], J. Meyer-ter-Vehn[8], R. Nietubyc[4], J. B. Pelka[4], K. Sokolowski-Tinten[9], N. Stojanovic[9], H. Wabnitz[10], K. Tiedtke[10], S. Toleikis[10], T. Tschentscher[10], U. Zastrau[11]

[1]Institute of Physics ASCR, Na Slovance 2, 182 21 Prague 8, Czech Republic
[2]Czech Technical University, Brehova 7, 115 19 Praha 1, Czech Republic
[3]Czech Technical University, Sitna 3160, 272 01 Kladno, Czech Republic
[4]Institute of Physics PAS, Al. Lotników 32/46, PL-02-668 Warsaw, Poland
[5]Charles University in Prague, Albertov 6, 128 43 Prague 2, Czech Republic
[6]Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, CA 94550, USA
[7]Uppsala University, Uppsala, SE-75124 Sweden
[8]Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, D-85748 Garching, Germany
[9]University of Essen, D-45117 Essen, Germany
[10]Deutsches Elektronen-Synchrotron DESY, Notkestrasse 85, D-22603 Hamburg, Germany
[11]University of Jena, D-07743 Jena, Germany

Some molecular solids are very sensitive to irradiation with pulsed XUV/X-Ray radiation. We proved experimentally that PMMA - poly (methyl methacrylate) can easily be ablated by a focused FLASH (Free-electron LASer in Hamburg [1]) beam. The craters formed in PMMA by the FEL pulses provide a reliable information on the beam profile. It can be seen in Fig. 1 that the laser-ablated area is very clean. The PMMA surface roughness as determined by the atomic force microscope (AFM) was (0.45±0.01) nm before the irradiation, whereas the roughness inside the crater is typically (3.72±0.06)nm. The roughness change is almost independent of fluence. Lateral thermal processes, e.g., melting or thermal diffusion, are not likely to play a key role in a certain fluence range. Therefore, the beam characteristics, e.g., beam diameter or spatial fluence distribution, may be determined from the crater characteristics.

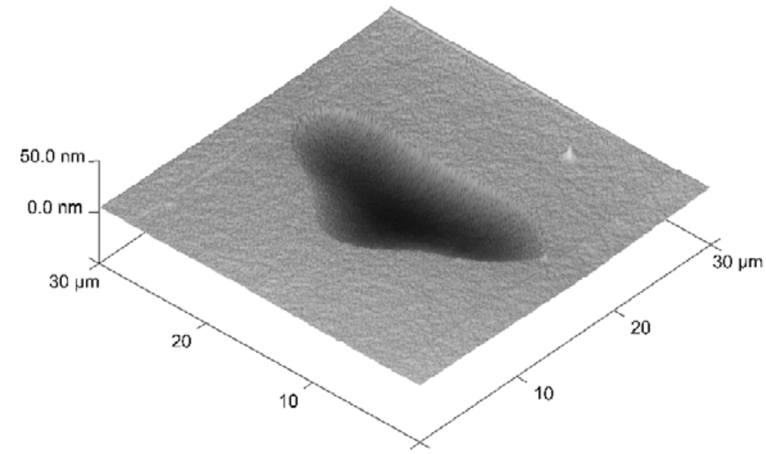

Fig. 1 - AFM image of a typical crater ablated in PMMA by highly attenuated, focused FLASH beam.

Liu's method [2], which we used for the analysis, is applied to surface damage data obtained by means of the Nomarski microscope (DIC - differential interference contrast) and AFM operated in the tapping mode. We assume the radiation attenuation length is independent of the laser intensity, the localized action of deposited energy in the material and the Gaussian temporal and spatial shapes of the FLASH pulses. The beam and ablation parameters are then calculated from fitting parameters of a linear regression $y = A+B\ln(E_{pulse})$ applied to the measured crater areas and the crater depths plotted in dependence on the pulse energy logarithm. For the spot-area analysis the focal spot area S_{foc} and the ablation threshold F_{th} are then linked through: $S_{foc} = B$, $F_{th} = \exp(-A/B)/S_{foc}$. Analogously, for the crater-depth analysis the attenuation length l_{at} and the ablation threshold F_{th} are given by: $l_{at} = B$, $F_{th} = \exp(-A/B)/S_{foc}$.

In our experiments, 500-nm layers of 495K PMMA spin-coated on 315-μm-thick silicon chips (Silson, UK) were used. The samples were positioned in an ultra-high vacuum interaction chamber and irradiated by a single ~25fs FLASH pulse at 32nm. The pulse energy varied in a wide interval using the gas attenuator and also due to shot-to-shot fluctuation of the SASE source. The beam was tightly focused on the sample surface

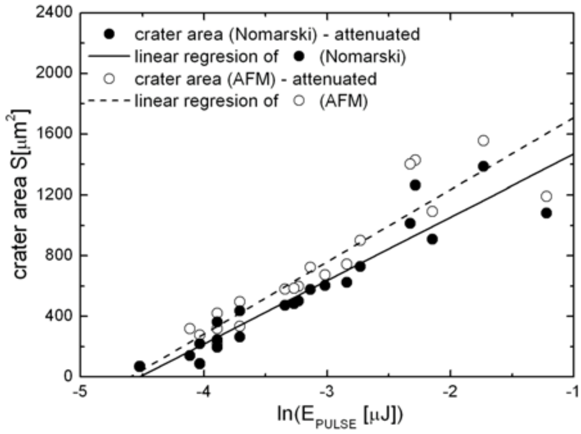

Fig. 2 - Dependence of ablated area on FLASH pulse energy.

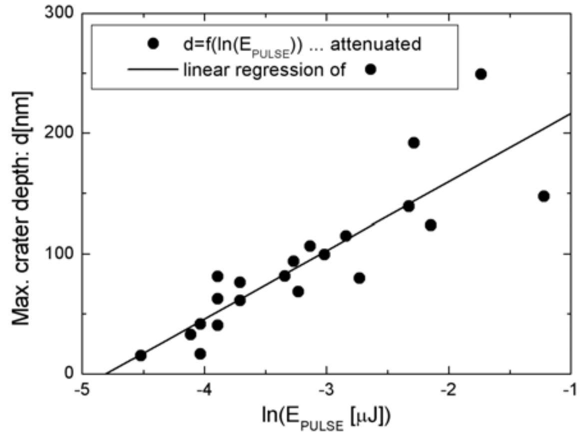

Fig. 3 - Dependence of ablation (etch) depth on FLASH pulse energy.

using a grazing incidence elliptical mirror with a focal length of 2m. A focal spot of 20μm in diameter follows from ray-tracing simulation of the optical system.

Figs. 2 and 3 show measured PMMA-crater areas and depths, respectively, as a function of pulse energy determined by GMD [3]. The lowest fluence required for a single-shot ablation damage to PMMA irradiated by 32-nm FEL radiation lies about at 2mJ·cm^{-2}. The full width at half maximum (FWHM) of the FEL beam is FWHM = $2\rho(\ln 2)^{1/2}$ = (19.9±0.5)μm. This value is in a good agreement with the spot diameter as calculated from the focusing system parameters and the beam characteristics. The crater-depth analysis yields l_{at} = (56.9±7.5)nm. The attenuation length agrees very well with the value of ~55nm measured in PMMA using a synchrotron radiation [4]. The PMMA ablation is under the given irradiation conditions extremely clean. There are no bubbles and/or micron sized surface imperfections usually attributed to the thermal modification of the PMMA surface, which could affect accuracy and reliability of this method of the beam spot characterization.

In conclusion, an ablative imprint of a focused FLASH beam is smooth and clearly visible even at low fluences, limited only by single-shot threshold fluence of ~2mJ·cm^{-2}. For low and medium pulse energies, when undesirable thermal and nonlinear effects are negligible, the 3-dimensional AFM-determined crater structure correlates well with a real beam profile. Thus PMMA may be utilized for "post mortem" fluence distribution imaging.

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