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Optical damage of multi-layer mirrors for UV-FEL resonator induced with intense pico-second pulse FELs and Nd:YLF lasers

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Abstract

Optical damage of multi-layer mirrors used in an ultraviolet free electron laser (UV-FEL) resonator at linac-based FEL has been observed. The peak power of the UV-FEL at the linac-based FEL is about 100 times as large as that of the ring-based FELs. The mirror degradation mechanism in the linac-based FEL therefore is entirely different from that of the ring-based FEL which has been reported. Several 0.2 mm diameter craters have been found on both surfaces of upstream and downstream Ta_2O_5/SiO_2 multi-layer mirrors of the resonator after 50 h UV-FEL oscillation at 310–370 nm. At each crater, several layers near the surface are crushed by ablation induced by the FEL. Results from both the X-ray micro-analysis (XMA) on the craters and luminescence analysis during ablation induced with the pico-second pulsed Nd:YLF laser, which is the same pulse format as the FEL, explain that the pico-second pulses of the laser affect the damages.

Keywords: Free electron laser; Dielectric multi-layer mirror; Degradation

1. Introduction

The UV-FEL facility of the Free Electron Laser Research Institute (FELI) has succeeded in lasing at UV-wavelength in 1995 and keeps a shortest wavelength world record of linac-based FELs by reaching 278 nm in June 1996 [1]. At the same time, a mirror degradation problem has occurred. While Au coated Cu mirrors are used for the infrared optical cavities, only dielectric multi-layer mirrors are used for the UV-FEL cavity in order to minimize low reflection losses [1]. The mirror loss is suppressed within 0.1% per pass.

Resonator mirror degradation in storage ring-based UV-FELs has been studied by the Super-ACO group [2–4], the TERAS & NIJI-IV group [5,6], the UV-SOR group [7] and the Duke Univ. group [8]. The Super-ACO group reported that the mirror degradation occurred with the thermal effect of the high synchrotron power (~20 W) and the UV through X-ray irradiation. The TERAS & NIJI-IV group stated that the mirror degradation is governed by photo-chemical reaction between the FEL beam and the gas in the mirror chamber on the mirror surface. Here the main reason for

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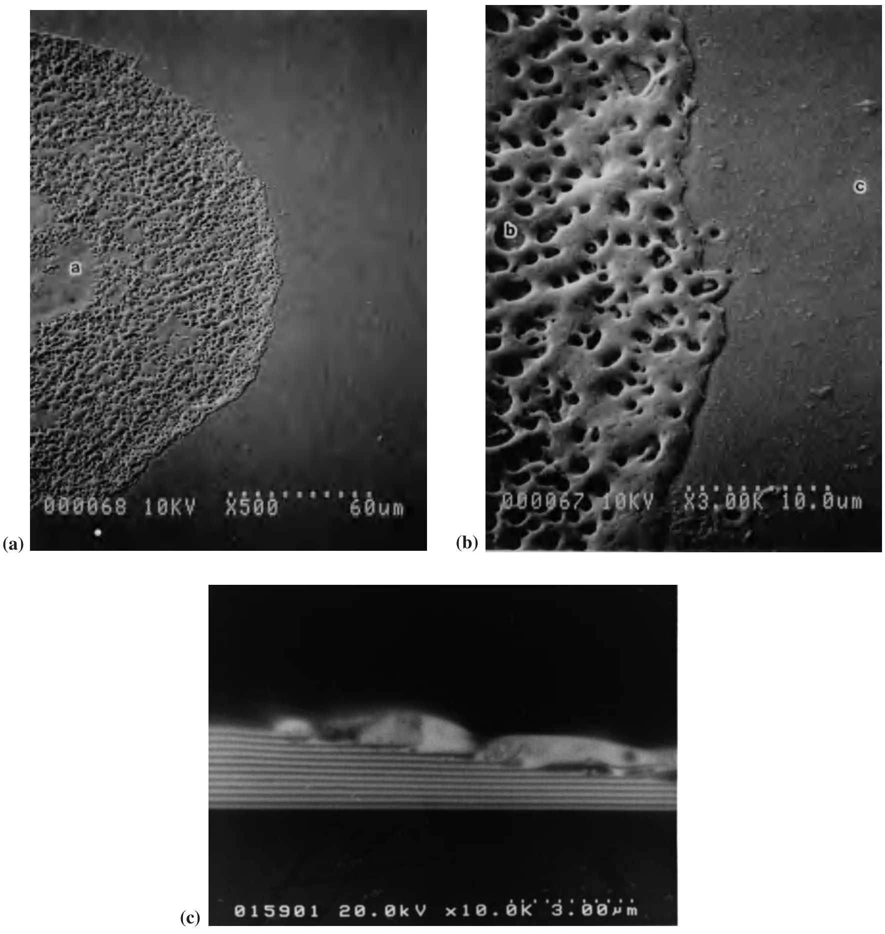
degradation is the deposition of chemical compounds by synchrotron radiation. Linac-based UV-FEL operation was reported for the Los Alamos on third harmonic FEL [9,10]; however, the degradation problem was not reported. While the peak powers of the storage ring-based FEL facilities are on the MW level, the FELI intra-cavity peak power is 0.9 GW and the peak intensity nearly reaches 6 GW/cm^2 at the inner-surface of the mirror [11]. Therefore the mechanism of the mirrors degradation is entirely different from the ring-based FELs mentioned above. This paper describes: (1) the first experience on degradation of a multi-layer mirror of Ta_2O_5/SiO_2 purely due to ablation by intracavity UV-FEL irradiation, and (2) X-ray micro-analysis (XMA) measurement on the damaged surface and luminescence measurement during Nd:YLF laser irradiation.

2. SEM observation of damage on the multi-layer mirror

In Ref. [12] it was briefly reported that the damage of the downstream resonator Ta_2O_5/SiO_2 mirror surface after about 50 h of operation at the FELI come from both intra-cavity FEL and bremsstrahlung radiation. The precise observation of the upstream mirror surface (Fig. 1) has revealed that the mechanism is ablation.



(a) (b) (c)

Fig. 1. SEM photographs of the damaged mirror surface. (a) Top view, (b) border of the damaged surface (close-up), and (c) cross-sectional view.

The cavity mirrors were optimized for the high reflectivity (~99%) to decrease the mirror loss. Two kinds of dielectric multi-layer coated mirrors have prepared for the UV-FEL resonator in order to cover a wide range of FEL oscillation wavelengths: Ta_2O_5/SiO_2 for 310–370 nm, and HfO_2/SiO_2 for 220–310 nm [13]. The reflection wavelength range is designed to be very narrow compared with a metal-coated mirror such as the Au coated Cu mirror. The multi-layer mirrors are deposited on the 30 mm diameters quartz (SiO_2) substrates and have 26 layers (alternately Ta_2O_5 and SiO_2 layers, 13 of each kind) with the $\lambda/4$ thickness. λ is the laser wavelength. The inner surface and the outer surface of the mirror are protected with the over coat layer and an anti-reflection coating, respectively. Total mirror thickness is 5 mm.

Fig. 1 shows SEM photographs of the damaged mirror: (a) top view, (b) border of the damage surface (close-up) and (c) cross-sectional view. About ten 200-μm diameter craters are observed on the mirror. The damages are represented on the surface with the round shape. In the top view the damaged surface clearly appears to be melt and ruined by the ablation. This kind of surface damaged is clearly different from the mirror degradation observed on the ring-based UV-FEL facility. In the cross-sectional view a white layer and a black layer are Ta_2O_5 and SiO_2, respectively. Half of the layers are melt and formed to a lump. If anything, the damage resembles a damage induced by a high power pulsed laser [14]. We can therefore presume that the mirror degradation comes from the damage due to the FEL ablation.

3. XMA analysis of the mirror surface

The mirror surface was studied with an X-ray micro-analysis (XMA). Top and bottom of the ablated crater and a normal surface are named (a), (b) and (c) in the Fig. 1, respectively. The results are shown in Fig. 2. On the bottom ablated crater the tantalum L_α emission at 8.3 keV is found to be much smaller than the crater rim (a) and undamaged surface (c). The silicon K_α and the tantalum M_α X-ray emission at 1.8 keV can hardly be distinguished because these energies are very similar; however, the peak intensities are same for the three surfaces. No other peaks, which could possibly come from the deposition of other material on the surface, are detected by the XMA analysis. This result indicates that most of the tantalum is evaporated from the mirror surface by the UV-FEL ablation.

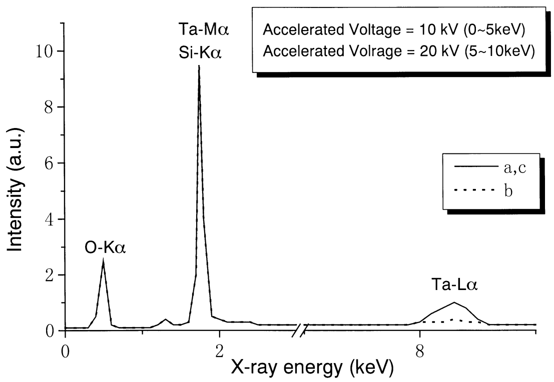


Fig. 2. XMA result from the damaged surface and the normal surface. Trace (a) was measured on the rim of the crater, (b) on the bottom, and (c) on an undamaged part of the surface.

A thermal effect theory explains that the laser induced damage threshold (LIDT) varies as $\sim\tau^{1/2}$, where τ is the laser pulse duration [15,16]. The LIDT of an ordinary commercial dielectric multilayer mirror is 0.3 J/cm^2 for a 10 ns pulsed laser [17]. Thus LIDTs of 7.3 J/cm^2 and 3.9 mJ/cm^2 are estimated for the macropulse (~6 μs) and the micropulse (~1.7 ps) of the FEL, respectively, on the basis of thermal effect theory. Since the fluences of the intracavity FEL macropulse and micropulse are 1.3 J/cm^2 and 10.2 mJ/cm^2, respectively, we conclude that the damage is induced by the picosecond FEL micropulses.

4. Luminescence analysis during the ablation

A Nd:YLF laser system (Nippon Electric Co.) has been used for ablation study, because it has a similar pulse format compared with the FELI FELs shown in Table 1 [16], although it was originally developed for a photo-cathode laser of an RF-gun [18]. The Nd:YLF laser can cause the

Table 1
Optical parameters of the UV-FEL and the Nd:YAG laser

Lasers	UV-FEL	Nd:YLF (3ω)
Wavelength	273–400 nm	351 nm (3ω)
Pulse format	1.7 ps, 22.3/88.9 MHz (micropulse)	~7 ps, 88.9 MHz (micropulse)
	~ 6 μs, 10 Hz (macropulse)	~20 μs, 10 Hz (macropulse)
Average power	~4 mW at 350 nm	~0.4 mW
Peak power	1.8 MW (out-cavity) at 350 nm	~3.2 MW
	0.9 GW (intra-cavity) at 350 nm	
Intensity (peak)	~6 GW/cm^2 at 350 nm	~ 6 GW/cm^2

ablation on the multi-layer mirror like the UV-FEL causes, therefore we can verify the phenomena of the mirror degradation in the UV-FEL mirror resonator. The peak intensity of the focused 351 nm Nd:YLF laser can reach the same order of that of the intracavity UV-FEL as described in Table 1.

We prepared a Czerney–Tunner type monochrometer (ORIEL-MS257) and an ICCD camera (InstaSpecIV) for spectral measurement of the luminescence comes from the ablation point in air. The ICCD camera can detect the 50 nm width spectra with 0.2 nm resolution at a time. Fig. 3 shows the persistent luminescence spectra from 610 to 970 nm, when the Ta_2O_5/SiO_2 multi-layer mirror is irradiated with the focused 351 nm Nd:YLF laser (3ω). In the figure we indicate the elements which lines are corresponding to the known wavelengths [19]. At 744 and 865 nm luminescence from nitrogen element (N) are observed. At 645 nm the luminescence from oxygen (O) is observed. At 742, 785 and 941 nm the luminescence from silicon element (Si) are observed. At 765 and 805 nm the luminescence from nitrogen molecule (N_2) are observed, because the ablation occurred. Main peaks of tantalum are out of range. The result indicates that the plasma (plume) induced with the FEL micropulse is formed on the mirror during the ablation.

5. Conclusion

At the linac-based FELI FEL facility the intense peak power of the FEL (~6 GW/cm^2) results in damage of the dielectric multi-layer mirror (Ta_2O_5/SiO_2) due to the ablation of tantalum. This damage mechanism is different from that found on ring-based FELs, where mirror degradation was caused by surface deposition of chemical compounds by the high average power of synchrotron irradiation. Moreover, the luminescence result of the ablation by the Nd:YLF laser pulse-formatted similarly with the UV-FEL and X-ray analysis

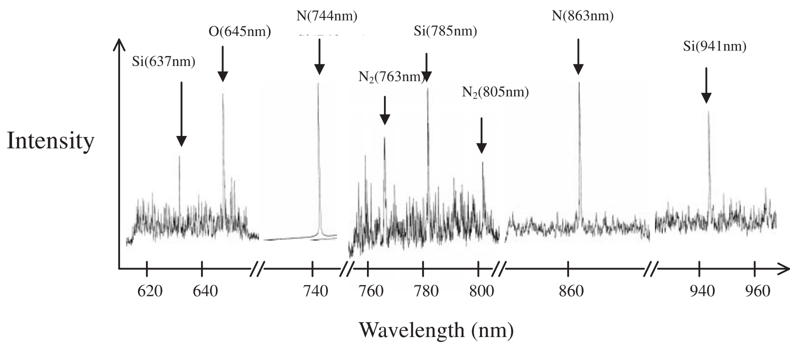


Fig. 3. Luminescence spectra from the Ta_2O_5/SiO_2 mirror with the 351 nm Nd:YLF laser irradiation. The wavelength resolution is 0.2 nm.

conclude that the ablation phenomena are induced with the pico-second FEL pulse.

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