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Characterization of non-Gaussian mid-infrared free-electron laser beams by the knife-edge method

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HIGHLIGHTS

- We measure the M^2 factor for the free-electron laser with a non-Gaussian profile.
- Fitting and smoothing of the knife-edge data work equally well.
- The obtained M^2 value turned out to be ∼1.1.
- The knife-edge results are consistent with the burn-pattern results.

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ABSTRACT

We report the characterization of mid-infrared free-electron laser (FEL) beams at the wavelength of 11 μm by the knife-edge method. From the knife-edge data we find that the FEL beam has a non-Gaussian shape. To represent the non-Gaussian beam shape we employ two methods: fitting the knife-edge data to some analytical functions with a few free parameters and numerical smoothing of the knife-edge data. Both methods work equally well. Using those data we can reconstruct the two-dimensional (2D) beam profiles at different positions around the focus by assuming that the 2D intensity distribution function is separable in *x* (horizontal) and *y* (vertical) directions. Using the 2D beam profiles at different positions around the focus, we find that the beam propagation factor (M^2 factor) is ∼1.1 in both *x* and *y* directions. As a cross-check, we also carry out the burn pattern experiment to find that the behavior of the focused FEL beam along the propagation is consistent with the results obtained by the knife-edge method.

1. Introduction

Since its first lasing in 1976 [1], FELs have attracted a lot of interests in various research areas due to their high power and large wavelength tunabilities [2]. The FEL we have at our institute, Kyoto University free-electron laser (KU-FEL), is an oscillator-type FEL at the mid-infrared wavelength of 5–13 μm with the macropulse repetition rate of 1 Hz [3]. Each macropulse has a duration of ∼1.5 μs and contains several thousands of micropulses with a duration of ∼0.6 ps and an interval of 350 ps between them. For many applications such as mid-infrared spectroscopy and nonlinear optics, it is crucial to have the knowledge on the micropulse duration, wavelength stability, and the spatial beam quality. For this reason we have recently measured the micropulse duration and wavelength stability of KU-FEL at 12 μm under the presence of unknown amount of chirp by a new method, which is a variant of the fringe-resolved autocorrelation [4], and the single-shot spectra of temporally selected micropulses from KU-FEL at 11 μm using the sum-frequency mixing technique [5]. Most recently, we have demonstrated that the KU-FEL pulses gated by a plasma mirror with *unusually long* (nanosecond) switching pulses have the high focusability [6], which results in nonlinear spectral broadening by focusing the beam into the nonlinear target. Although the fact that we have observed the nonlinear spectral broadening clearly implies that the high intensity has been achieved upon focusing, we still do not know the spatial beam quality of the incident FEL beam.

To measure the spatial beam quality, the most straightforward way is to use a commercial M^2 analyzer. Unfortunately there is no commercial M^2 analyzers available for the beam at the wavelength of > 1.8 μm, in particular with a very low repetition rate. The second choice is to use a 2D-array detector (beam profiler) and measure the beam profiles at different positions along the propagation. However, one must carry out a detailed analysis by themselves,

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since the commercial beam profilers do not have the function to determine the M^2 value. The above two methods are rather expensive (more than 20,000 USD), and hence such convenient commercial devices are not always available to the FEL users. The third choice is to build a device by ourselves based on more conventional methods such as slit scan [7], pinhole scan [8], and knife-edge scan [9,10]. Among these techniques, the knife-edge method is most commonly used due to high signal-to-noise ratio and excellent spatial resolution. Indeed, the knife-edge measurements have been performed for the oscillator-type FELs in a continuous pulse-train mode [11,12]. If better accuracy is desired, one can carry out a tomographic beam profile measurement by the knife-edge scan in many (usually more than 7) directions, and reconstruct the 2D beam profile using the inverse Radon transform [13].

In this paper, we report the characterization of non-Gaussian mid-infrared (~11 μm) FEL beam by the 2D knife-edge method. Known the fact that analytical methods developed for Gaussian beams under the knife-edge measurement [10,14,15] do not work, the new ingredient in this work is the detailed report of the data analysis for non-Gaussian beam, which would be useful not only in the mid-IR but also in the other wavelength range such as extreme ultraviolet and X-ray.

For the data analysis, we employ two methods to represent non-Gaussian beam shape. One is fitting method to represent the real beam shape by some simple analytical function with a few free parameters to be fitted, and the other is smoothing method so that the derivatives of the knife-edge signals can be smoothly represented. It turns out that both methods work equally well, and we can reconstruct the 2D beam profiles by taking the derivatives of the knife-edge signals under the assumption that the 2D intensity distribution function is separable in two (horizontal and vertical) directions. Then, by making use of the 2D beam profiles reconstructed at different positions around the focus, we can obtain the variation of the beam diameter around the focus. Again, special attention has to be paid to deduce the beam diameter from the 2D beam profiles due to non-Gaussian feature of KU-FEL beams. Finally we deduce the M^2 factors to be about 1.1 in both x and y directions. As a cross-check, we also carry out the burn pattern measurement, and find that the burn patterns are consistent with the results by the knife-edge method. We note that the ablative imprints, which are similar to the burn patterns but with three-dimensional information by atomic force microscopy, have been used to characterize the spot size of X-ray laser beams [16]. More sophisticated online diagnostics system using extreme ultraviolet Hartmann sensors has been developed for FLASH [17].

2. Experimental setup

The experimental setup for knife-edge measurements is shown in Fig. 1(a) for the case of x direction scan, where x, y, and z axes stand for the horizontal, vertical, and the laser propagation directions, respectively. The laser beam from the output of the KU-FEL with the beam diameter of ~14 mm (for $1/e^2$) at the central wavelength of 11 μm is focused by a $f = 150$ mm ZnSe lens. A knife-edge mounted on a three-axis translational stage is placed in the xy plane near the focus with the edge oriented to the y direction. The energy of the FEL pulse transmitted past the knife-edge is measured by the signal detector (Gentec. EO, QE8SP-I-BL-BNC), which we call E_{sig}. The shot-to-shot fluctuation of macropulse energy is typically ±16% during the measurement, and it is not very different from the normal distribution. To reduce the influence of shot-to-shot fluctuation of FEL pulse energy, we monitor the FEL pulse energy before the lens with a reference detector (Newport, 818E-10-50-S), which we call E_{ref}. After averaging over 20 shots at each position we record the normalized transmitted energy $S_1 = E_{sig}/E_{ref}$

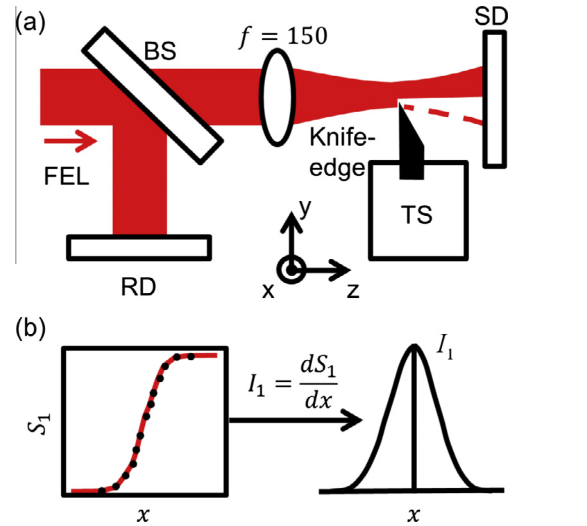

Fig. 1. (a) Experimental setup (top view). The BS, SD, RD, and TS stand for the beam splitter, signal detector, reference detector and translational stage, respectively. (b) Illustration of the transmitted energy S_1 as a function of x and its derivative.

during the scan in x direction. For the central scan range where S_1 changes from 20% to 80% with respect to that of the unblocked beam, the step size is 10 μm, while at the beginning and end of the scan range, the step size is 20 μm. Fig. 1(b) illustrates the shape of S_1 (left) and its derivative, dS_1/dx (right). We repeat the similar measurement at 8 different positions along the z direction around the focus. We also carry out the similar knife-edge measurements in y direction, while the normalized transmitted energy is called S_2.

It is known that FELs, in particular in a pulsed-mode, may exhibit non-negligible shot-to-shot pointing jitter, which may influence the results of the knife-edge measurement. During the data acquisition of S_1 (S_2) for a given position defined by x_n (y_n) and z, we find that the shot-to-shot differences of the values of $S_1(x_n)$ ($S_2(y_n)$) are almost the same for all x_n (y_n)'s, and take the value of ~0.05, while S_1 (S_2) is ~2 when the knife cut half of the beam (see Fig. 3). To estimate the pointing jitter and its influence on the knife-edge measurement, the largest values of $|S_1(x_n) - S_1(x_{n+1})|$ and $|S_2(y_n) - S_2(y_{n+1})|$ are listed in Table 1 for different z, when the transmitted energy is between 20% and 80%. Note that the step size for this range is 10 μm, i.e., $x_{n+1} - x_n = 10\ \mu m$. Needless to say $|S_1(x_n + 1) - S_1(x_n)|$ ($|S_2(y_n + 1) - S_2(y_n)|$) becomes the largest value when the knife cut nearly half of the beam (see Fig. 1(b)).

From Table 1, we find that even when the beam diameter is relatively large, i.e., ~700 μm at z = 150 and 166 mm (see Fig. 8), the shot-to-shot differences of the values of $S_1(x_n)$ ($S_2(y_n)$), which is ~0.05, is smaller than the largest value of $|S_1(x_{n+1}) - S_1(x_n)|$ ($|S_2(y_{n+1}) - S_2(y_n)|$) at the same z. This implies that we will not miss the peak of dS_1/dx (dS_2/dy) even under the presence of shot-to-

Table 1
Largest values of $|S_1(x_{n+1}) - S_1(x_n)|$ and $|S_2(y_{n+1}) - S_2(y_n)|$ for different z.

z (mm)	$max[|S_1(x_n + 1) - S_1(x_n)|]$	$max[|S_2(y_n + 1) - S_2(y_n)|]$
150	0.10	0.15
154	0.28	0.25
155	0.30	0.30
156	0.35	0.42
158	0.42	0.45
160	0.30	0.35
162	0.23	0.23
166	0.12	0.13