Photonic device, Astrophysics, Catalysis, Medicine and drug

Extreme focusing of X-ray free-electron laser using ultra-precise mirror optics

Research Center for Precision Engineering, Graduate School of Engineering

Assistant Professor Jumpei Yamada

Researchmap https://researchmap.jp/J_Y190325?lang=en

Abstract

A mirror optical device fabricated with nanometer-level shape accuracy and atomic-level surface roughness works as an "ideal X-ray lens." By proposing and demonstrating a unique X-ray mirror optical system, diffraction-limited focusing performance has been achieved in the hard X-ray wavelengths regime. This enabled a focused spot size of 7 nanometers and a peak intensity of 10^{22} W/cm² at the X-ray free-electron laser (XFEL), representing the highest X-ray intensity and smallest XFEL focal size. The focusing system has also been applied to the generation of "bare atomic nuclei" by strong photoionization of solid-density chromium.

Background & Results

X-rays, since their discovery by W. C. Röntgen, have been essential in numerous fields such as medicine, biology, and materials science, revealing key insights like DNA's double-helix structure. The recently developed X-ray free-electron laser (XFEL) is an almost fully coherent and extraordinarily brilliant X-ray laser source. At SACLA, Japanese XFEL source, XFELs have been focused down to sizes as small as 100~50 nm with peak intensities reaching 10^{20} W/cm², enabling cutting-edge experiments such as single-particle protein crystallography and ultrafast pump-and-probe measurements.

If the XFEL could be focused below 10 nm (sub-10 nm), it would achieve photon densities comparable to the strongest lasers across the entire spectral regime, long anticipated for advanced applications. However, the XFEL sub-10 nm focusing has faced obstacles in optical design, component fabrication, and beam evaluation. Here, we achieved a 7×7 nm focal spot and 10^{22} W/cm² intensity, marking the world-smallest XFEL focus size and the highest intensity, by applying our unique X-ray mirror optical systems, wavefront correction techniques, and precision focus diagnosis methods.

The focusing system has been extensively applied to practical XFEL experiments. For example, fluorescence observations of solid-density chromium (Cr) revealed emissions of Lyman (Ly) line, indicating the generation of hydrogen-like Cr ions with only one remaining electron. Moreover, the behavior of the Ly spectra at high intensity foci indicates the formation of a fully ionized state in which all electrons are excited. This breakthrough holds promise for fields such as astrophysics, atomic physics, and X-ray nonlinear optics, as well as single-molecule protein structure analysis without crystallization.

Significance of the research and Future perspective

The newly developed 7 nm-focused XFEL with an intensity of 10^{22} W/cm² suggests the potential to replicate stellar ionization states on Earth and achieve electron temperatures exceeding 100 million K through X-ray excitation. This advancement could enable comparisons with cosmic X-ray spectra and investigations into the early stages of thermonuclear fusion, promising applications in astrophysics, atomic physics, and high-field science. Moreover, the achieved XFEL intensity enables the exploration of high-order X-ray nonlinear optical phenomena and single-molecule protein structure analysis without crystallization, possibly revolutionizing measurement and optical technologies beyond current limits.

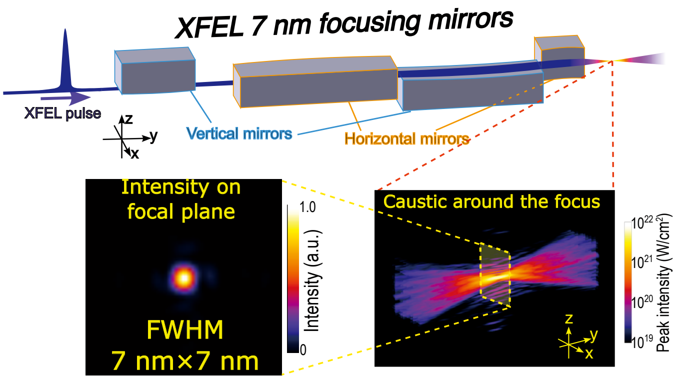

Fig. 1. Schematics of extreme focusing system at X-ray free-electron laser.

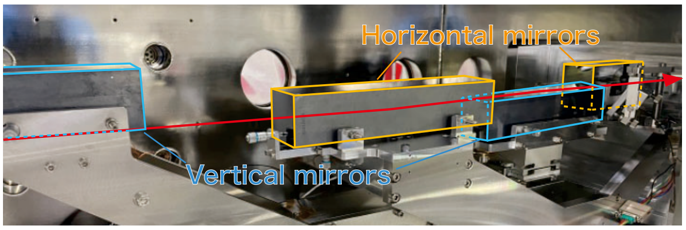

Fig. 2. X-ray mirrors for 7 nm focusing, equipped in a vacuum chamber.

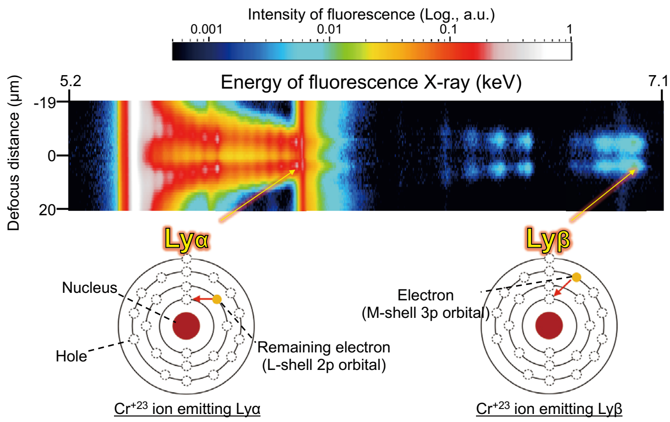

Fig. 3. Results of atomic line spectra and Ly lines emitted from a solid Cr sample.

Patent	
Treatise	Yamada, Jumpei; Yabashi, Makina; Yamauchi, Kazuto et al. Extreme focusing of hard X-ray free-electron laser pulses enables 7 nm focus width and 10^{22} W cm^{-2} intensity. Nature Photonics. 2024, 18, 685-690. doi: 10.1038/s41566-024-01411-4
URL	
Keyword	X-ray mirror, X-ray free-electron laser, X-ray focusing