Achieving microfocus of the 13.5-nm FLASH beam for exploring matter under extreme conditions


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We have focused a beam (BL3) of FLASH (Free-electron LAser in Hamburg: 13.5 nm, 15fs, 10μJ, 5Hz) using a fine polished off-axis parabola having a focal length of 270 mm and coated with a Mo/Si-ML giving a reflectivity of 67% at 13.5 nm. The OAP was mounted and aligned with a picomotor control six-axis gimbel. Beam imprints on PMMA were used to measure focus and the focused beam was used to create isochoric heating of various slab targets. Results show the focal spot has a diameter of ∼1μm. Observations were correlated with simulations of best focus to provide further relevant information.

The experimental platform at FLASH is shown in schematic form in Fig. 1. FLASH was operating at a wavelength of 13.5 nm, i.e. a photon energy of 92 eV for these experiments. The laser produced pulses of XUV radiation containing between 10 and 50 μJ per pulse in a pulse length of order 15 fs (1) at a repetition rate of 5 Hz. The highly-collimated beam of diameter 3mm was focussed onto solid samples using a Mo/Si multi-layer-coated off-axis parabola with a focal length of 270 mm, and an initial reflectivity of 67 %.

Zerodur off-axis parabolid (OAP) substrates 50 mm in diameter were fine polished to the surface specification that the first 36 Zernike polynomials should yield 1 nm rms. Additionally, and RMS surface roughness should be 0.3 nm for mid spatial frequencies of 1 mm to 1 micron and for high spatial frequencies of 1 micron to 50 nm. After fine polish, the figure (Z1-Z36) was measured to be 0.3nm RMS with MSFR = 0.148nm RMS and HSFR = 0.177nm RMS (Fig. 2a). This RMS figure error yields a Strehl ratio of 0.92 (MSFR, HSFR errors have no visible effect on focusing performance). Simulations of the focused beam using the FLASH specifications for BL3 (Source distance to BL3: 74 m, divergence of the beam: 100μrad FWHM, beam diameter at source: ~100μm, working distance from optic to focus: ≥ 250 mm) are presented in Fig. 2b. The simulation shows that the ultimate focused spot diameter is 0.3 um for his OAP. However, experimental limiting factors affecting the ultimate focus include (1) optic alignment and (2) quality of incoming beam.

The Mo/Si multilayer coated mirrors were characterized at the Advanced Light Source B6.3.2. (2) The 13.5 nm mirror performance as a function of its angle and wavelength are reported in detail elsewhere. (3)
Experimentally proving focus was accomplished by imprinting the focused single-shot beam profile on a 5 µm PMMA/Si(100) target (ablation threshold for PMMA - 50 mJ/cm²). In-situ observation of best OAP alignment and focus was accomplished using a long-range microscope to determine focal spot diameter as a function of absolute target position, thus varying the XUV intensity in the regime $10^{13} - 10^{16}$ W/cm². After many iterations, ex-situ Nomarski microscopy and AFM were used to characterize the imprinted beam profile and thus focus. Results are presented in Fig. 3. These results show that ≤ 2 µm focus was achieved with the aligned OAP optic. The observed focal spot is circular and shows no sign of astigmatism.

This focused XUV laser beam now allows us to begin exploring matter under extreme conditions. Our collaboration produced solid-density plasmas with unique properties by a volumetric heating of Al slab targets. Optical emission spectra of the expanding plasma plume were collected and transparency induced in solid density aluminum was studied. (4) Manipulating matter with photoelectric resonant excitation and understanding the dynamics of photo-induced phase transitions can provide unique data on the strength, density of states (DOS), kinetics, dislocation mechanics (type, generation, mobility) and transport properties (energy, particle). Developing advanced characterization capabilities for probing matter under extreme conditions are important to the emerging field of High Energy Density Science (HEDS).

In conclusion, new specifications for optics elements are required for 4th generation sources that account for slope error, wavefront distortion, and Strehl ratio. Better metrology is also required for better grazing incidence optics to attain tight focus. The Maréchal criteria for good quality optics: Strehl ratio > 0.8 (ratio of the maximum intensity at the focus in the presence of distortions, divided by the intensity that would be obtained if no distortion were present); corresponds to RMS roughness < 0.5 nm.

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