# X-ray Imaging beyond the limits

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The intense and extremely brief pulses generated by X-ray free-electron lasers open up new opportunities for the structural analysis of biological objects. The short pulses allow us to literally out-run the effects of radiation damage, which otherwise limits the imaging of soft matter at high resolution. We are carrying out a program of research to characterize and apply the method of “diffraction before destruction” to push beyond both the radiation and technological limits of the conventional methods, as well as to develop new capabilities in time-resolved imaging.

Our experiments at FLASH have continued to extend our capabilities of our instrumentation with the goal of achieving higher hit rates of flowing aerosols of reproducible samples, improved photon detectors, and increased pulse intensities achieved with new X-ray optics. High intensity is required to achieve the highest resolution, since the diffraction efficiency decreases rapidly with increasing scattering angle (or resolution). In addition to the latest generation of high-efficiency aerosol injector, produced at Uppsala University, we have developed sub-micron liquid jets that have been tested at FLASH in preparation for operations of the facility at photon energies above the carbon *K* edge (that is, in the water window).

Figure 1: The multilayer-coated off-axis parabola (left) and an optical differential interference micrograph of a single-shot crater created near the focal plane (right).

We maximise pulse intensity by focusing x-rays to an area as small as practical wtih a normal incidence multilayer coated optic, shown in Fig. 1. A super-polished off-axis parabola substrate was coated with a relatively narrow bandwidth multilayer to selectively reflect only the desired wavelength of 6.8 nm. The periodic multilayer consisted of Mo and $B_4C$ layers with a bilayer period of 3.4 nm. This multilayer system underwent a thorough investigation on reflectivity, stress and thermal properties before being used in FLASH experiments. The surface quality of the off-axis parabola is quantified as < 0.2 nm rms surface deviation in high- and mid-spatial-frequency components, and a low frequency figure error of 0.2 nm. The figure error causes aberrations of the optic, whereas the higher frequencies lead to scattering that reduces the effective reflectivity. With the extraordinarily low roughness the multilayer reflectivity was measured at 21% for this 6.8 nm wavelength. The focusing optic produced a sub-micron spot, as was determined by creating single-shot X-ray-generated craters in smooth surfaces at the focal plane. To find the optimum focal distance and to measure the focused beam size we made a series of exposures on a flat PMMA sample, such as that shown in Fig. 1. The craters in PMMA were subsequently characterized ex-situ by Nomarski differential interference microscopy and with an atomic force microscope. The crater shapes allowed us to reconstruct the beam profile and extract the intensities. We estimate that the focal spot was ~700 nm in diameter and that the pulse intensities above $5 \times 10^{17}$ W/cm$^2$ were achieved. This is about 50 times higher intensity than we could previously reach at FLASH (using the beamline optics) and similar to intensities of single-particle imaging experiments carried out at LCLS (at shorter wavelengths of 0.6 nm). Development of a normal incidence multilayer-coated off-axis parabola for 4.3 nm wavelength is now in progress.

Our high-intensity system was commissioned in beamtime at FLASH in 2011, but the remaining shifts to carry out single particle measurements will be carried out in 2012. Some diffraction data from single Rhodobacter Spheroides cells caught on the fly are shown in Fig. 2.

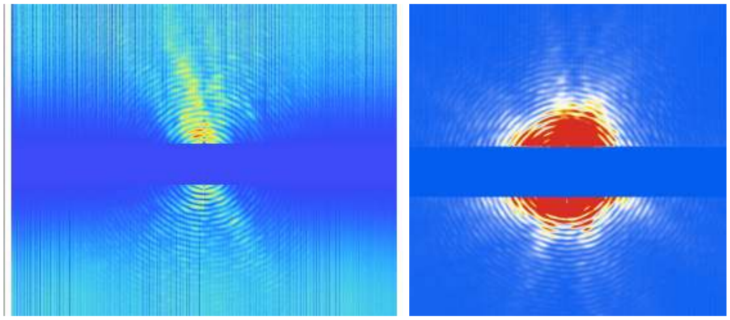

Figure 2: Single-shot diffraction patterns from Rhodobacter Spheroides (a photosynthetic purple bacterium) from Oxford University.