High-Resolution Diffractive Imaging at FLASH

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We have carried out a program of research in high-resolution single-pulse coherent diffractive imaging at the FLASH free-electron laser. The intense focused FEL pulse gives a high-resolution low-noise coherent diffraction pattern of an object before that object turns into a plasma and explodes. In particular we are developing imaging of biological specimens beyond conventional radiation damage resolution limits, developing imaging of ultrafast processes, and testing methods to perform single-particle imaging.

In coherent diffractive imaging, a focused FEL pulse illuminates the isolated sample, which scatters the light to give a coherent and continuous diffraction pattern. Spatial and temporal coherence are necessary to ensure that the scattered light waves from all scattering centres of the sample are correlated when they interfere at the detector, and the diffraction pattern must be sampled finely enough so that highest frequencies in the pattern (from the largest separation of points in the object) are not aliased. These conditions allow the diffraction pattern to be phased and then inverted to give a high-resolution image of the sample. There are advantages to this mode of microscopy when using FEL pulses: the retrieved image is complex-valued, giving image contrast both by absorption and phase-shifting or refractive properties of the sample; the diffraction pattern is insensitive to the transverse sample position; and "focusing" of the image is performed as part of the computational reconstruction process. These properties make diffractive imaging ideal for studying objects that are injected into vacuum on the fly, and for high-resolution single-shot imaging where the sample does not survive the beam.

Experiments were carried out at 13.5 nm wavelength, using a diffraction camera consisting of a multilayer-coated mirror, which reflects the diffraction pattern onto a bare CCD [1,2]. Our apparatus can position fixed samples on silicon nitride window arrays into the beam, or shoot particles across the beam. Examples are shown in Fig. 1. The test object was etched with a focused ion beam (FIB) after a few latex spheres of 145 nm were deposited on the silicon nitride membrane. Both the FIB object and the two latex spheres were reconstructed to a resolution of 40 nm. We also performed the first ever reconstruction of a single cell using a single FEL pulse. The single cell organism is *Spiroplasma melliferum*, an elongated helical bacteria, and the image was reconstructed to 70 nm resolution.

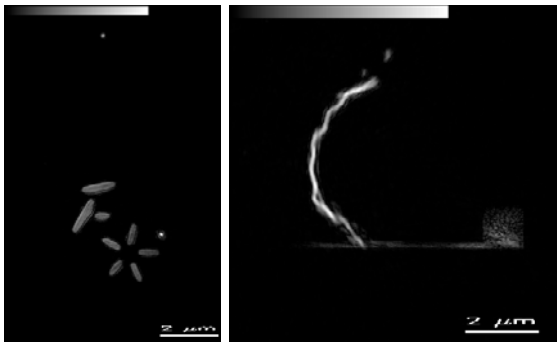

Fig. 1 (left) Reconstructed image of a test object with two 145-nm diameter spheres, reconstructed to 40-nm resolution. (right) Reconstructed image of a spiroplasma cell. Both images were reconstructed from single-pulse FEL coherent diffraction patterns at 13.5 nm wavelength.

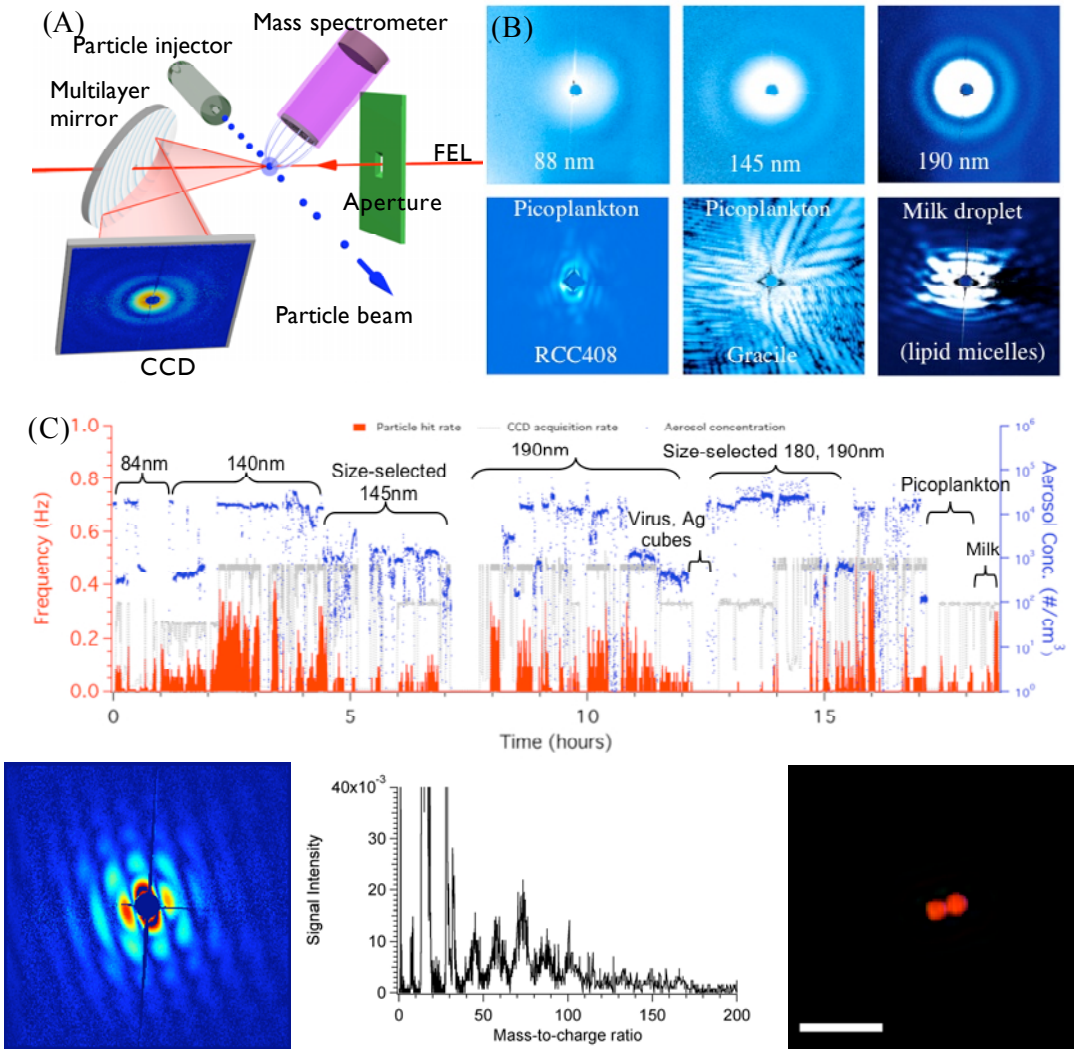

Fig. 2. (A) A schematic of the diffraction camera for FLASH set up in particle injection mode. (B) Example images of spherical nanoparticles and complex biological samples such as single cells and lipid micelles. (C) Data stream from our first particle injection shift in March 2007. (D) Diffraction image collected during injection of megadalton scaffolded DNA complexes with a tamper of sucrose. (E) Time-of-flight mass spectrometer detected ions specific to this type of particle. (F) The image reconstruction showed that two particles were irradiated simultaneously by a single FLASH pulse (scalebar is 1 micron).

We successfully developed and demonstrated a particle injection system and diagnostics [3]. The injector operates as a continuously refreshed beam of free nanoparticles delivered through a differentially pumped aerodynamic lens, in a "shotgun" mode (unsynchronized to the FLASH pulses). We operated with pulse trains of 10 μs spacing. The particles, travelling faster than 100 m/s, were only hit by a single pulse. A summary of some results is shown in Fig. 2. During one run we operated the injector continuously for 18.7 hours, performing 26 sample changes with 14 different samples (Fig. 2 C). The CCD collected images continuously and 1873 of 16639 patterns contained particle scattering information, giving an average hit rate of 0.05 Hz (including all sample change down time). Samples included size-selected latex spheres, Ag cubes, DNA nanocomplexes, picoplankton, and lipid micelles. We have reconstructed images of injected whole hydrated picoplankton cells and latex dimers. Our results confirm the feasibility of single-particle diffractive imaging.

References

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