Applications of Free Electron Laser light: atomic structure, molecular dynamics and quantum control

Kevin C. Prince

Elettra Sincrotrone Trieste, AREA Science Park, Trieste, Italy

Optical lasers and synchrotron radiation sources are versatile tools for investigating the physics and chemistry of matter. Free Electron Lasers (FELs) combine some of the properties of both sources, and produce light with short wavelengths characteristic of synchrotrons, combined with typical laser properties such as ultrafast time structure, extreme peak power and coherence. This opens up new scientific opportunities in a wide range of experiments.

A major driving force for very short wavelength FELs is x-ray crystallography, where the goal is to measure the atomic structure of single proteins. Conventional x-ray crystallography at synchrotrons has solved numerous protein structures, but requires a macroscopic crystal and not all proteins can be prepared in this form. The method using FELs has been successfully applied to nanocrystals [1] and work is continuing. The technique uses the extremely high power and ultrashort pulse duration of FELs to generate a diffraction signal before the sample is destroyed by the x-rays.

Another application of the ultrashort time structure is pump-probe spectroscopy, in which a sample (for example a molecule) is excited (pumped) by a pulse of light, and then probed by a second pulse. In these dynamical studies, information is obtained about how the molecule relaxes on the femtosecond scale after absorbing energy. A recent example is an experiment at FERMI in which a small molecule, acetylacetone, was pumped by UV light, and then probed by FEL light [2]. The energy absorbed is sufficient to break chemical bonds, that is, the molecule fragments, and the detailed information obtained from photoemission spectra allow accurate theoretical modelling of the process. This kind of study has applications in photochemistry and photobiology.

Optical lasers have been used for quantum control, in which coherent light is used to manipulate the outcome of the interaction of light with matter. For example, a photochemical reaction may be steered to produce one product in preference to another. The light from FERMI has been used to achieve quantum control, in this case by manipulating the direction in which electrons are emitted from an atom, by using two wavelengths and controlling the phase difference between them [3].

Finally some perspectives on future developments and applications of FEL light will be given.

References:
[1] H. N. Chapman *et al.*, Nature **470**, 73 (2011).
[2] R. Squibb *et al.*, Nature Comm. **9**, 63 (2018).
[3] K. C. Prince *et al.*, Nature Photon. **10**, 176 (2016).