Artemis: synchronised XUV and laser sources for ultrafast time-resolved science

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Introduction

Artemis is a new facility based on high repetition rate, few optical cycle tuneable laser sources - one of which is used to produce ultra-fast XUV pulses through high harmonic generation. These synchronised sources are coupled to a number of beam-lines with synchrotron style end-stations for materials science and atomic and molecular physics and chemistry. The aim is to combine frontier femtosecond optical and synchrotron technologies and enable new science in the emerging field of ultrafast X-rays. Bringing together expertise from the laser and synchrotron communities is particularly important with the advent of X-ray free electron lasers (FELs), such as the UK's proposed NLS project. Artemis is already being used to test out high harmonic generation schemes for FELs.

Laser beamlines

The Artemis facility provides a variety of ultrafast, synchronised laser beamlines which can be configured flexibly either to generate XUV or as pump and probe pulses. The core of the facility is a 14 mJ, 30 fs, 1 kHz Ti:Sapphire CPA system operating at 780 nm. Part of the output energy is split and spectrally broadened in a gas-filled hollow fibre and recompressed using chirped mirrors to give sub-10 fs pulses. This technology was successfully implemented in Astra TA1, where 0.3 mJ, 10 fs pulses were routinely available. The laser system is carrier-envelope phase controlled [1], enabling us to provide few-cycle pulses with precisely defined optical electric fields. We are able to lock the carrier-envelope phase of the laser system at full power to 310 mrad (measured with 10 ms acquisition time) for over an hour (Figure 2).

Part of the 14 mJ, 30 fs output can also be used to drive a widely tuneable OPA system, which will provide 30-100 fs pulses from 250 nm to 20 microns. The signal and idler stage have been installed and IR pulse energies of up to 1 mJ at 1350 nm are available (Figure 3). Measurements of the pulse duration of the 1300 nm radiation show that the pulse length is ~ 40 fs. The shot-to-shot energy stability of the output is 3% rms with <2% rms energy stability from the pump laser. Coverage over the full wavelength range will be available from summer 2009, with energies in the 10s of microjoule range at 250 nm and 10 micron.

Figure 1. View of the Artemis facility showing the laser beamlines and the XUV generation chamber.

XUV beamlines

XUV radiation in the wavelength range 10-100 nm (10-100 eV) is produced through high harmonic generation (HHG) in a gas target. The resulting XUV

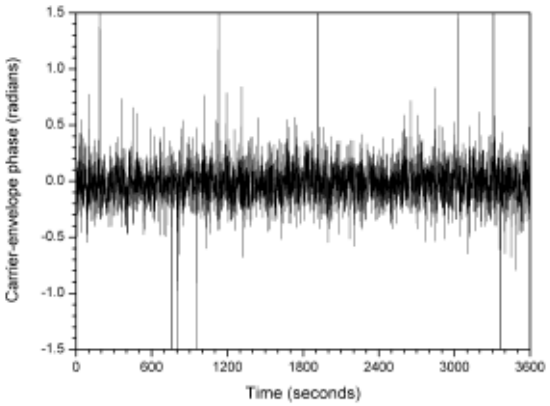

Figure 2. Measurement of the CEP of the laser system at 13.5 mJ showing an rms value of 310 mrad over a full hour.

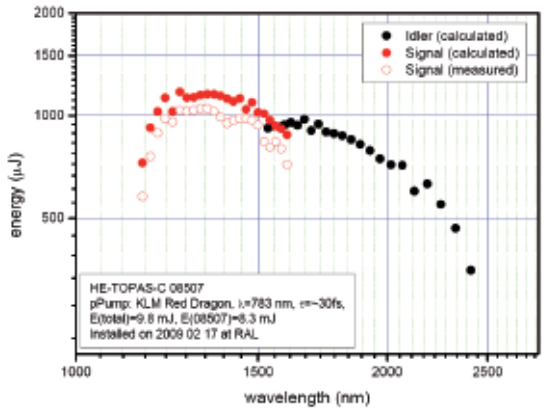

Figure 3 (a). Calibrated output of the OPA system

radiation has similar pulse-duration to the drive laser pulse and is synchronised to the drive laser pulse with sub-fs resolution. With conversion efficiencies up to 10^{-6} at 30 eV, a photon flux of up to 10^{11} photons s^{-1} per harmonic is achievable. Figure 4a below shows a typical raw spectrum obtained with 1300 nm radiation in Argon. Fig 4b shows calibrated spectra from Ar with 30 fs, 800 nm pulses and CO_2 with 1300 nm pulses. Using the 1300 nm drive laser, harmonics up to 80 eV can be seen, with the short wavelength cut-off limited by the edge of the detector.

The XUV radiation can be spectrally characterised using a flat-field spectrometer. This detects radiation from 20 eV to 80 eV with a theoretical resolution of about 200. The detector consists of a 40 mm double stage MCP with a phosphor screen attached and a 14-bit camera. This instrument will also enable measurement of the carrier-envelope phase of the drive laser pulses[2].

The XUV generated is delivered to the interaction stations in two beamlines – one for broadband and one for monochromatised XUV pulses (Figure 5). Both of the beamlines provide spectral filtering with a selection of thin metallic filters, focusing and recombination with pump or probe laser beams.

For experiments requiring wavelength and bandwidth selection, the harmonics will pass through a state of the art high resolution XUV monochromator for ultrashort pulses. This has been designed and built in collaboration with the LUXOR Laboratory of the Italian National Council of Research. The monochromator enables a single harmonic to be selected from the spectrum, while maintaining the pulselength to within 10 fs.

The output of the monochromator is imaged onto the interaction region with 1:1 magnification using a gold, toroidal mirror at grazing incidence. In the broadband XUV beamline, a similar mirror images the high harmonic source. As grazing incidence toroidal mirrors can introduce large amounts of coma, the spot-size of the XUV pulses will be measured by imaging the fluorescence induced by the XUV pulses on a crystal such as Cerium-doped YAG that fluoresces in the visible[3]. Recombination of the XUV pulses with a pump or probe laser beam can be achieved through several techniques. The XUV can be passed through a gold mirror with a small central hole, while reflecting the much larger laser beam off it.

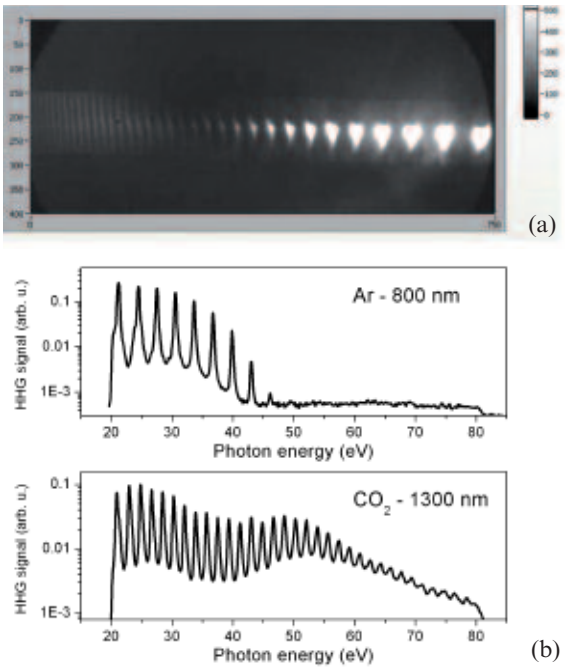

Figure 4 (a). HHG spectrum detected with the flat-field spectrometer using a 1300 nm drive laser pulse and (b) calibrated spectra showing that harmonics up to at least 80 eV can be produced.

Alternatively, the laser beam can be transmitted through a thin silicon flat at Brewster's angle and XUV wavelengths >25 nm reflected.

The Materials Science Station

The materials science station consists of a UHV (< 2×10^{-10} mbar) chamber, a liquid helium-cooled five-axis manipulator and a hemispherical analyser equipped with a 2-dimensional detector for energy- and angle-resolved photoemission experiments (Figure 6).

Monochromatic XUV pulses can be combined on the sample with 10 fs IR pulses and the broadly tuneable output from the OPA with variable time delay. The availability of short pulses and multiple wavelengths extends the station's capabilities by offering pump-probe techniques for time-resolved photoemission

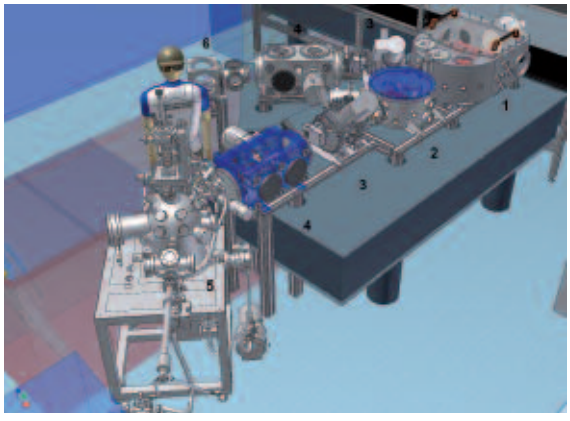

Figure 5. Engineering drawing of the XUV beamlines. Chamber #1 is the XUV generation chamber, #2 is the monochromator, #3 is the flat-field spectrometer (shown in both of its possible locations), #4 are toroidal mirror chambers, #5 is the materials science station and #6 shows the location of the AMO station.

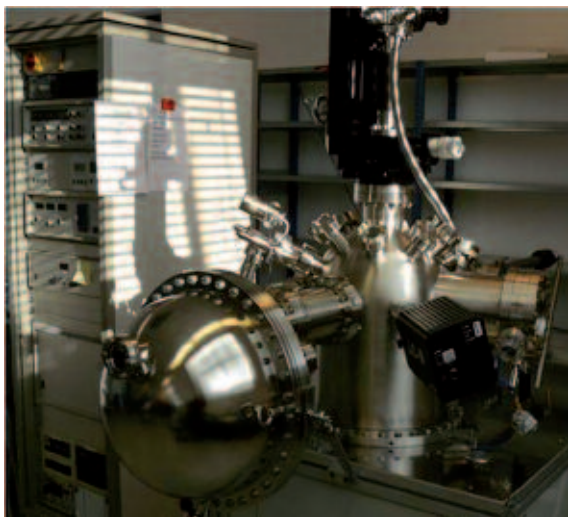

Figure 6. The Materials Science Station, showing the hemispherical electron analyser.

experiments to investigate coherent control and Fermi surface dynamics in complex oxides, non-adiabatic melting of charge order and Mott-gap dynamics as well as ultra-fast core-level photoemission.

The manipulator is designed to be able to both heat samples up to temperatures of 1000 K and to cool them down to temperatures below 20 K. Data taken at the factory shows that the sample can actually be cooled down to 14 K in just half an hour (Figure 7).

The station consists of a spherical main chamber constructed from mu-metal, to reduce the effect of stray magnetic fields. Attached to the main chamber is a separate load-lock system which greatly increases sample turn-around time, reducing the down-time that is associated with vacuum pumping and bake-out. A magnetic transfer arm allows the sample to be easily transferred from the separate load-lock chamber to the sample manipulator. The high-resolution manipulator offers the opportunity for spatial and angular mapping of samples.

The chamber includes a LEED for characterisation of the surface. A helium discharge lamp will be available for off-line alignment of the analyser and calibration of the energy resolution. In the future, we hope to include provision for a wide-range of sample preparation techniques, such as an ion gun for sample cleaning and evaporators and sputterers.

Atomic and Molecular Physics Station

The atomic and molecular physics chamber (Figure 8) will be designed for experiments on gas targets. This interaction station will permit experiments such as studies of the dynamics of aligned molecules, control of electron recollisions, time-resolved photoelectron imaging of excited state molecular processes, and Coulomb explosion imaging of molecular wavepackets. Future development of the molecular beam source will allow studies on clusters and molecules of biological interest.

The interaction station consists of two coupled chambers, with a molecular beam source in the lower chamber and a velocity-map imaging (VMI) detector for ions and electrons in the upper section.

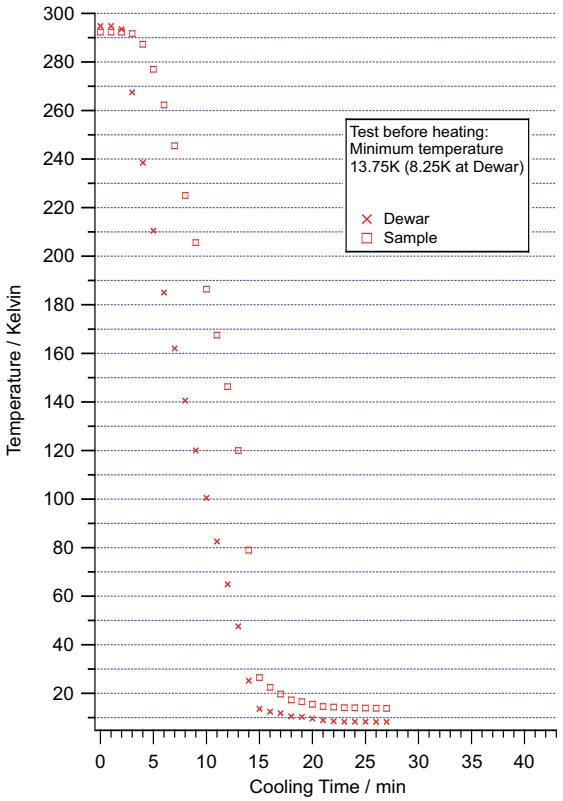

Figure 7. Measurement of the temperature of the sample in the MatSci chamber showing that it gets below 14 K in 30 minutes

The molecular beam source can be fitted with either a continuous flow nozzle or a kHz gas-jet. The gas is ejected upwards and then passes through a skimmer. The skimmer provides differential pumping, while minimising turbulence to the gas flowing through it. The source chamber is pumped by two 2800 litres/second turbo pumps, which will enable a vacuum of better than 10^{-4} mbar to be maintained in the source chamber during gas flow. We expect that rotational temperatures below 10 K will be achieved for molecular gases. Production of large clusters of atoms or molecules will also be possible, with some modification of the gas nozzle.

In the interaction region of the VMI, the cool, collimated beam of target gas intercepts the laser or XUV pulse. The molecule or cluster is ionised by the laser and fragments. The ions or electrons produced are accelerated by a series of electrodes onto an imaging microchannel plate. The flight path is enclosed in mu-metal to shield the charged particles from stray magnetic fields. The electrodes are carefully designed so that ions (or electrons) with the same initial velocity but created in different parts of the interaction region arrive at the same point on the detector[4]. By applying an inversion algorithm to the resulting image, the original 3D velocity distribution of the particles can be recovered. The VMI detector also has the advantage that particles ejected at all emission angles can be collected, meaning that the full angular distribution can be measured without the need to rotate either the detector or the laser polarisation.

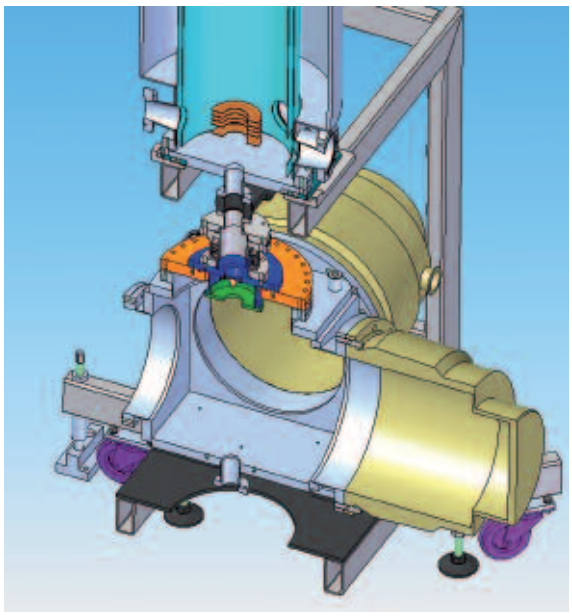

Figure 8. Engineering drawing showing a cross-section of the AMO station with the molecular beam chamber located underneath the velocity-map imaging detector.

Facility progress and future developments

The Artemis project was funded through a £1.5M Facility Development grant. The laser beamlines, XUV generation chamber, monochromator and flat-field spectrometer are now available for users. The first user experiments began in July 2008. XUV beamlines and science stations will come online in 2009.

In the longer term, we hope to be able to provide isolated attosecond pulses using the broadband XUV beamline, which has been designed to be compatible with a future attosecond upgrade. The spin-resolved science station will move to Artemis in 2011 to provide the capability of spin-resolved photoemission spectroscopy on solids. An upgrade of the laser system to increase the repetition-rate to ~100 kHz is also under consideration.

References

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