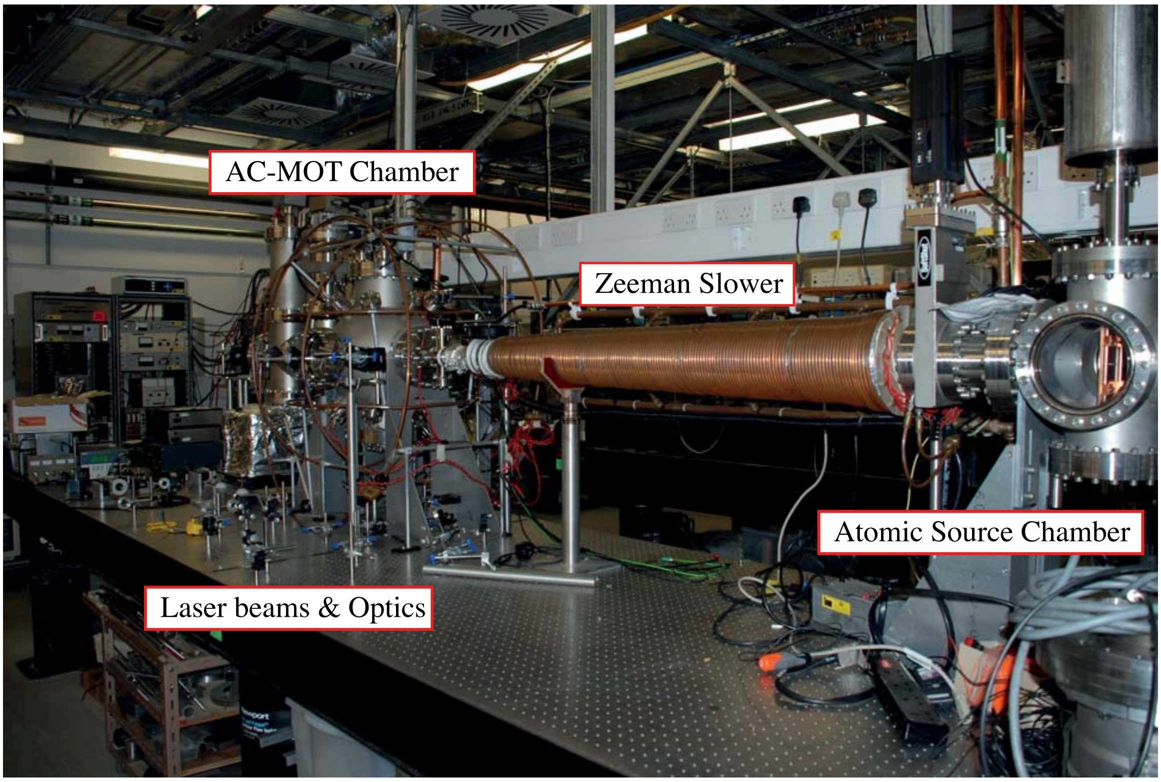
Title: Laser cooling and manipulation of atoms
Supervisor: Professor Andrew Murray

It is possible to control atomic motion using laser beams of well defined energy, since the selective absorption and emission of photons must be accompanied by a change in momentum of both the laser field and atom. Spontaneous emission allows atoms to be cooled to temperatures less than 1mK, whereas evaporative cooling techniques can further cool atoms to temperatures only a few nK above absolute zero. These atoms make up new states of matter, which are studied for their quantum effects.

In this project, atom cooling and trapping experiments are undertaken using a high intensity cold atom beam source developed in Manchester, as shown below. Experiments include electron impact collision studies from cold atoms, production of ultra-cold electrons beams from cold atoms, and the study of the fundamental properties of the cold atoms that are produced. A new type of atom trap (the AC-MOT) was invented in Manchester[1]. This uses high power audio amplifiers to drive current through the trapping coils, the polarization of the six molasses laser beams being adjusted in synchronicity with the audio signal. This new type of trap can be switched on and off more than 300 times faster than the more conventional DC-MOT, allowing new types of experiments to be conducted. These include the study of electron impact and laser excitation and ionization, where the unique nature of cold atoms allows new high precision measurements to be made. We can exploit the very low momentum of the targets to accurately define an ionizing collision, we can laser-excite the atoms to highly excited Rydberg states prior to super-elastic scattering of an electron from these targets, or we can photo-ionize the targets and study the ion and electrons that emerge.



One of the two atom cooling and trapping instruments in Manchester, showing the source chamber (right), Zeeman slower (centre) and trapping chamber (left) where collision and ionization experiments are carried out.

A second project using cold atoms is to develop a new source of ultra-cold electrons from laser-cooled Rb atoms (see project entitled: *Research and development of an ultra-cold high brightness electron source*). These projects are carried out in the state of the art laboratories located in the Photon Science Institute, using the very high finesse laser systems located there.

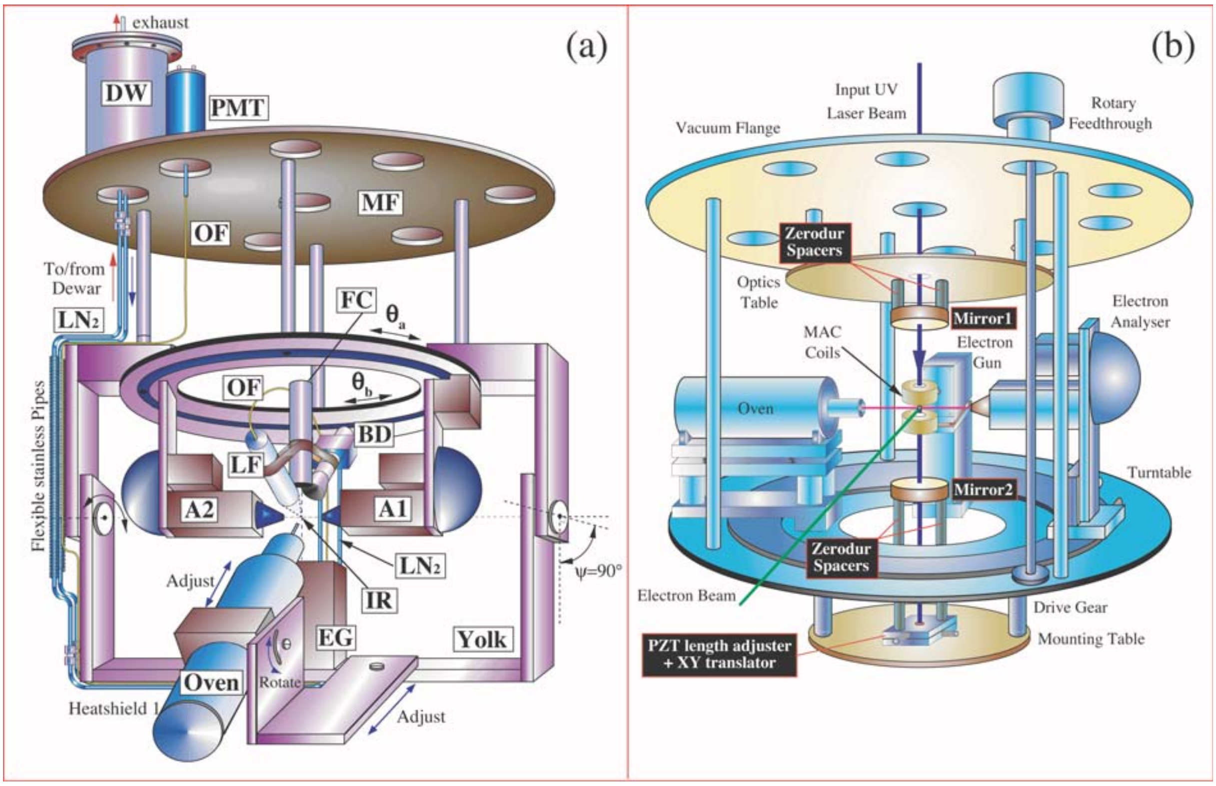
[1] M J Harvey and A J Murray, *Phys. Rev. Lett.* **101**, 173201(2008).

Title: Ionization & Excitation of Atoms Prepared by Laser Radiation (3 spectrometers)
Supervisor: Professor Andrew Murray

In these projects atomic or molecular targets are prepared in an excited state prior to electron impact. The incident electron of well-controlled momentum either ionizes the target, excites the target to a higher level or may super-elastically scatter from the target (ie the electron gains energy as the target relaxes back to the ground state). In each process the target state is controlled by the laser beam, which allows the 'shape' of the atom to be modified prior to the collision.

In the ionization experiments (shown in figure (a) below) an incident electron scatters from and ionizes the target, leading to two electrons in the final state. These electrons are detected and time-correlated with sub-ns accuracy. It then becomes possible to determine the reaction from *individual* atoms, and to measure the ionization probability as a function of the scattering angle for comparison to quantum collision theories developed by colleagues throughout the world. New experiments are being carried out where a target atom is excited and aligned by a CW laser, the atom then being ionized by the electrons. This type of interaction has not been studied before our work in Manchester[1], and we closely collaborate with colleagues in the USA, UK, Canada and Australia who model these complex interactions using sophisticated new quantum theories.

In the excitation experiments (figure (b)) we adopt *time reversal* methods to reveal highly precise information about the scattering process. In these experiments a laser defines the 'shape' of the electron charge cloud prior to electron impact, and we measure the rate of super-elastically scattered electrons as a function of the scattering angle and target shape. In this way experiments can be conducted thousands of times faster than is possible using conventional 'coincidence' methods. New experiments are underway which adopt a resonant enhancement optical cavity around the interaction region so that the intensity of the incident laser radiation can be increased by up to a factor of 200[2]. In this way we study atoms of technological and scientific interest, which are important due to their electronic structure[3]. Results from these experiments are then compared to quantum calculations produced by theoretical groups throughout the world.



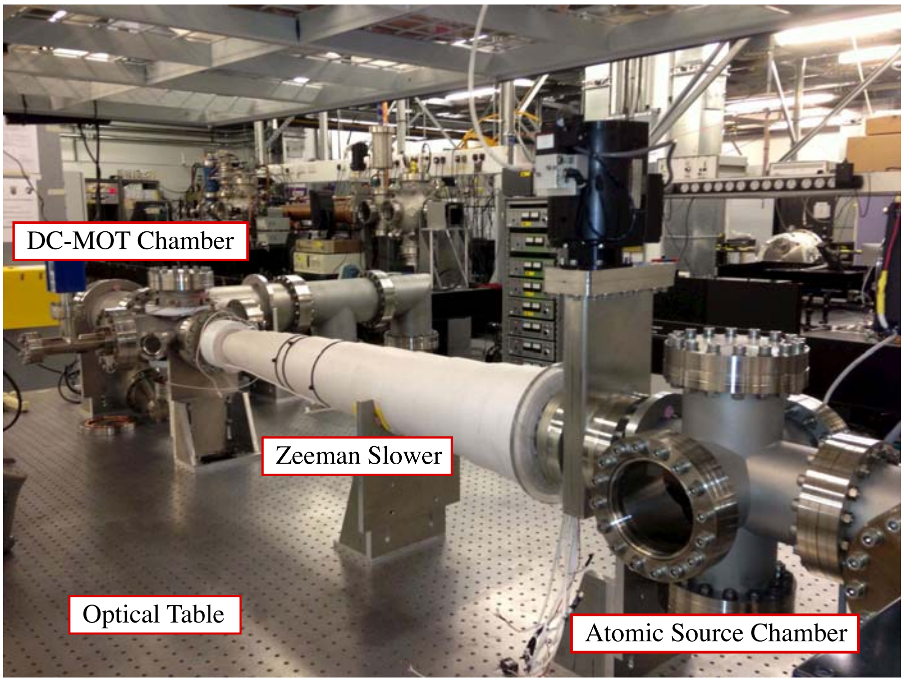
Two of the electron spectrometers for ionization and excitation studies of laser-prepared targets developed in Manchester. In (a), two detectors (A1,2) are used to detect electrons arising from the interaction (an e,2e) process). In (b), a Magnetic Angle Changing (MAC) device controls the direction of incident and super-elastically scattered electrons from laser prepared targets, excited in a resonance enhancement cavity (Mirrors 1 & 2).

[1] K L Nixon and A J Murray, *Phys. Rev. Lett.* **106** 123201 (2011)
[2] M J Hussey, S Jhumka and A J Murray, *Phys. Rev. A* **86** 042705 (2012)
[3] S Jhumka, K L Nixon, M Hussey and A J Murray, *Phys. Rev. A* **87** 052714 (2013)

Title: Development of an ultra-cold high-brightness electron source for new accelerators, free electron lasers & high-resolution electron diffraction studies
Supervisors: Professor Andrew Murray, Dr Guoxing Xia, Dr Will Bertsche

Development of an ultra-cold, high-brightness electron source is a world-leading initiative at the University of Manchester. This source offers unique opportunities to address a range of topics from fundamental research on ultra-cold plasmas and electron microscopes, through to technology applications ranging from vastly improved accelerators to novel materials characterization. This is a rapidly expanding topic internationally[1-4], and this work will contribute significant new ideas to this emerging field.

In this work (see figure below), laser-atom cooling and trapping methods are used to prepare a high density ensemble of cold rubidium atoms in a conventional Magneto Optical Trap (DC-MOT), before being injected into a new type of trap invented in Manchester[5], the AC-MOT (not shown - see project entitled *Laser Cooling and Manipulation of Atoms* for details). Cold atoms stored in the DC-MOT will be transferred using a confining laser to the AC-MOT, where the experiments take place. Several high-resolution continuous wave tuneable laser beams will trap the atoms, cool them to micro-Kelvin temperatures, manipulate them into an excited state and then photo-ionize the excited ensemble. This will create an ultra-cold high-density plasma consisting of Rb^+ ions and cold electrons. The electrons will then be extracted from the plasma using electrostatic optics, before acceleration to high energy for injection as a focused beam into different experiments[6].



The new cooling and trapping source being built in Manchester to produce an ultra-cold electron beam for injection into new types of accelerators, Free Electron Lasers and for materials characterisation using electron diffraction. The source will produce an electron beam with an energy resolution several orders of magnitude better than conventional sources.

This is a multidisciplinary area involving atomic and laser physics, plasma physics and accelerator physics. Students will work on the preparation and optimisation of the cold electron source, as well as on the electron acceleration, transportation and injection of the cold electron beam into new experiments. Once the electron beam has been fully characterised, it will be used as a source in new types of accelerators and Free Electron Lasers, as well as for probing materials using electron diffraction techniques. In each study an increase in resolution of several orders of magnitude is expected, compared to the conventional sources used today. This new cold electron source will hence deliver a new way forward in accelerator science, in X-ray laser production and in materials characterisation.

[1] A J McCulloch et al, *Nat. Comm*. **4**, 1692 (2013).
[2] W J Engelen et al, *Nat. Comm*. **4**, 1693 (2013).
[3] A J McCulloch et al, *Nature Physics* **7**, 785 (2011).
[4] B J Claessens et al, *Phys. Rev. Lett*. **95**, 164801 (2005).
[5] M J Harvey and A J Murray, *Phys. Rev. Lett.* **101**, 173201(2008).
[6] G. Xia, M Harvey, A J Murray, W Bertsche, R Appleby and S Chattopadhyay, *Proceedings of the International Particle Accelerator Conference* (2013).