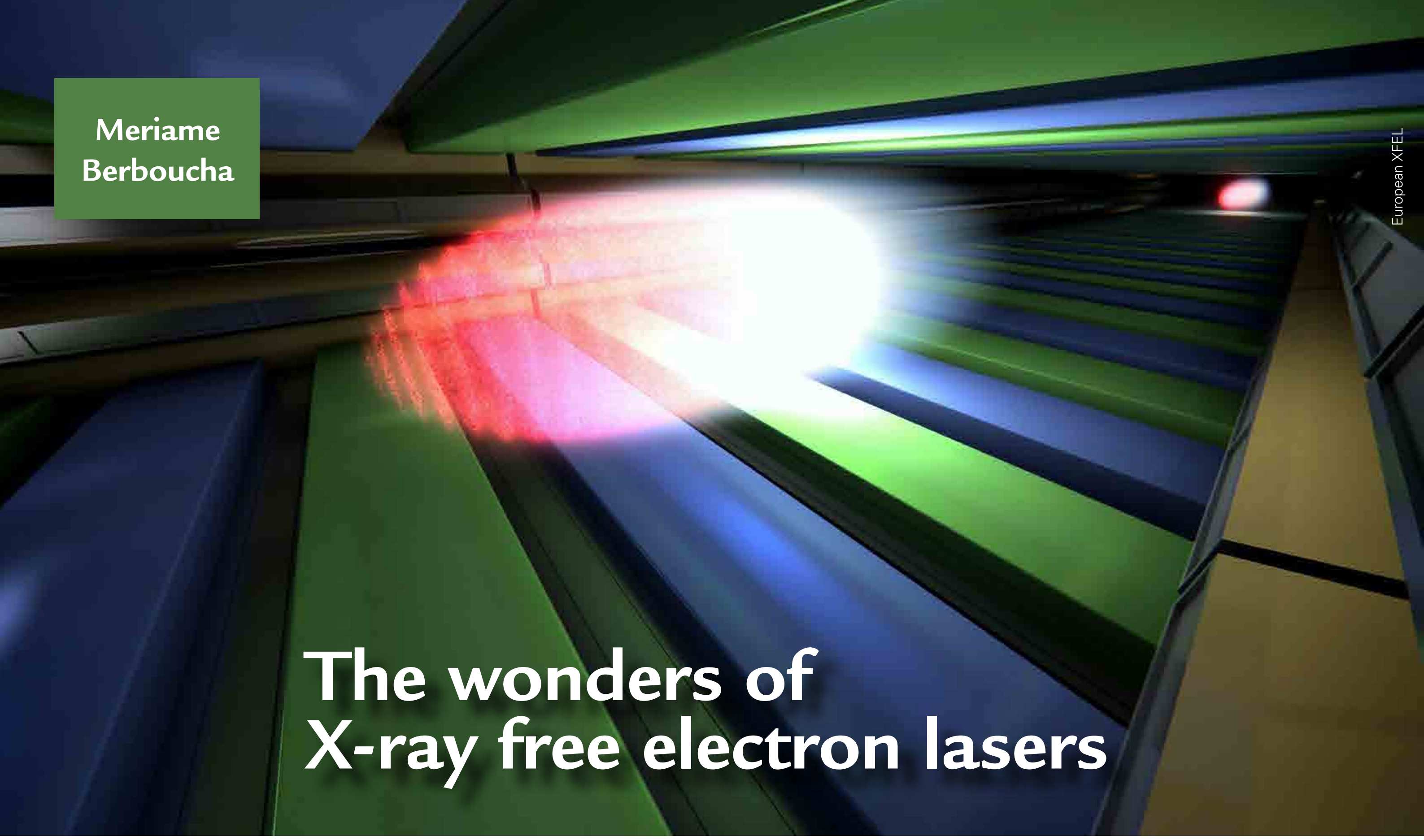
Meriame Berbouncha



The wonders of X-ray free electron lasers

Simulation of a laser flash generated in an XFEL undulator

Key words
laser
X-rays
electrons
radiation

Unravelling the complex molecular structure of proteins and viruses, taking snapshots of atoms and molecules during chemical reactions – these are just some of the many things we can do with an ***X-ray free electron laser****. With this, we can reveal the fundamental processes occurring in materials, living things and technology, helping us find out more about the world we live in.*

Laser light

You will be familiar with lasers used in laser pointers and in supermarket checkouts. These produce beams of visible light. There are several special things about this light:

- It is collimated – the beam is very narrow so that it spreads out only very slowly.
- It is monochromatic - all the waves have the same frequency.
- It is coherent - all the waves are in phase with each other.

What is an X-ray free electron laser?

An X-ray free electron laser (XFEL) is a type of laser that is typically hundreds of metres long. It uses 'wiggling' electrons to generate laser light with very short wavelengths.

So how does an X-ray free electron laser work? An XFEL begins with an electron beam. The electron beam is generated by 'boiling' off electrons from a metal with a laser. These electrons are then accelerated in special cavities known as resonators. In a resonator microwaves transfer energy to the electrons causing them to speed up to close to the speed of light. These resonators are superconducting which means that when they are cooled down to a very cold temperature (-271°C) they have zero electrical resistance. As a result, all the electrical power from the resonator is transferred to the electrons.

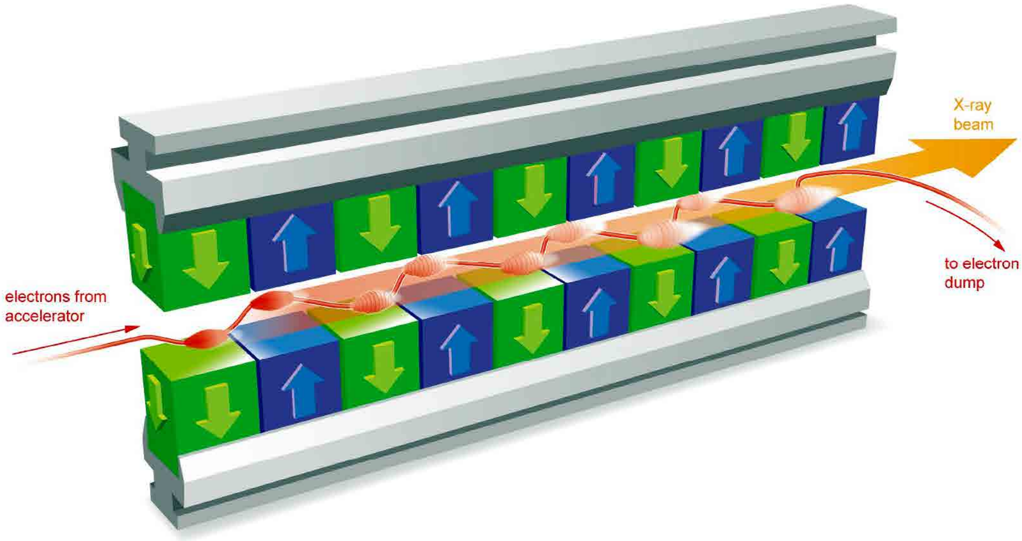
Now that the electrons are up to higher energies they pass through a magnetic structure with alternating north and south poles called an undulator where the electrons wiggle from side to side, almost as if they were on a tight slalom course. The 'wiggling' electrons are accelerating because they are changing direction and so they emit radiation, in this case X-rays.

The X-rays are much faster than the electrons and as the radiation overtakes the electrons they interact with the electrons and cause some of the electrons to accelerate and others to slow down. This leads to bunching where the electrons are organised into a series of thin disks. This is a very important property because the electrons in a given disk emit light that is coherent like the visible light from a laser. These disks normally take a bit of time to form and so the undulators are typically hundreds of meters long.

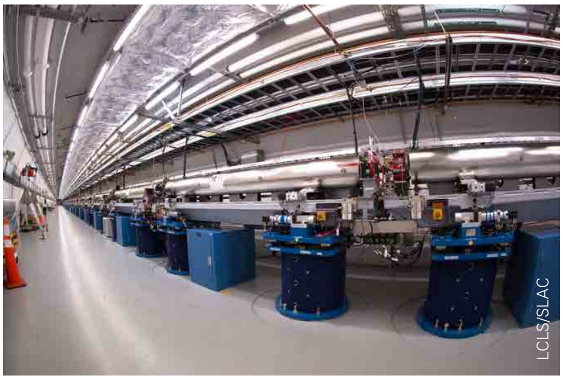
A final magnetic field is used to deflect the electrons from the electron-X-ray beam into a dump, leaving a train of ultra-short and ultra-bright pulses of X-rays. These X-ray flashes have similar properties to the light from a laser, namely, it is coherent and (almost) monochromatic. One of the great things about X-ray free electron lasers is that they are tuneable over a wide range of frequencies so we can use them for a wide range of science.

'Laser' stands for Light Amplification by Stimulated Emission of Radiation

European XFEL



In the undulator of an XFEL, magnetic fields force the electrons to wiggle from side to side. This causes them to emit X-rays. The electrons bunch together into flat discs so that the radiation they produce is coherent, like the light from a laser.



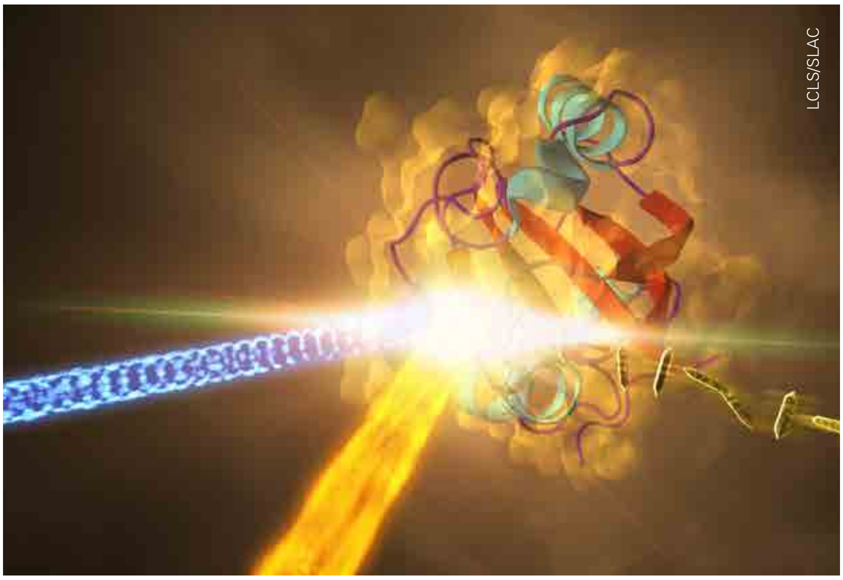
LCLS/SLAC

The undulator hall at LCLS, SLAC National Accelerator Laboratory, California, USA. Each undulator contains 224 magnets with alternating poles which force the electrons to wiggle and produce X-rays.

What use is an XFEL?

XFELs can be used to answer some fundamental questions and allow us to probe the very small scales of our world. This is because the wavelength of X-rays is very short (typically a billionth of a metre!) and so we can see very small objects. Also, each pulse only lasts for quadrillionths of a second which is short enough to study samples before they are damaged by the very bright light. Here are just some of the things we can find out about the world we live in with XFELs:

Photosynthesis and other chemical reactions – researchers have been using XFELs to study photosynthesis, one of the most important chemical reactions on Earth. They can take snapshots of these processes and turn them into science-y movies! Additionally, we can gain understanding of the crucial steps required for chemical reactions to occur which could, for instance, improve our ability to produce fuels and other industrial chemicals in more efficient and controllable ways.



LCLS/SLAC

This is an illustration of a protein from photosynthetic bacteria that changes shape in response to light. It was investigated during an experiment at LCLS, SLAC National Accelerator Laboratory, California, USA.

Electronics – scientists are looking into ways of controlling the magnetic and electronic properties of certain electronic materials with ultrashort pulses of light. As a result, we could have very fast, low-energy computer memory chips.

Matter in extreme conditions – we can create extremely hot and dense conditions which can help us understand the environment inside the cores of stars and planets. This will allow us to have a better understanding of fusion, aiding our quest of achieving fusion on Earth and generating clean, unlimited power to all of its inhabitants.

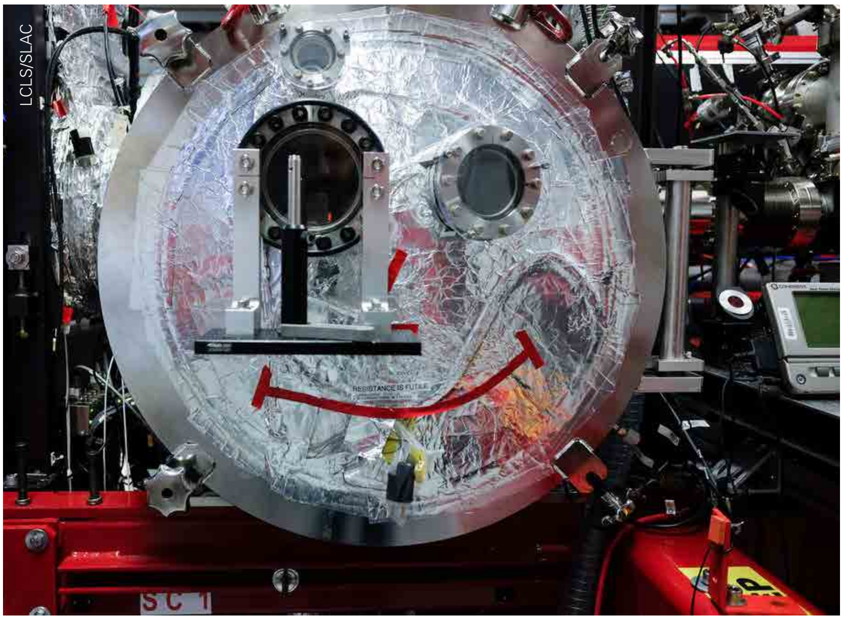
Inside us – we can determine the structures of proteins and as a result study biological structures, in particular those vital for disease and its treatment. This could lead the way to drug development and better treatment for diseases.

World's biggest XFEL

The largest XFEL in the world is located in the beautiful state of California in the U.S. at SLAC National Accelerator Laboratory. Linac Coherent Light Source (LCLS) is about 4 km long in total – that's the size of 40 football pitches length-ways!

Bird's eye view of SLAC, where the highlighted region in the diagram is LCLS. The experimental hutches are the rooms to the far right of the image. The linear accelerator (linac) is on the far left and is the largest linac in the world.

LCLS has six specialised experimental hutches where the X-ray laser is used for a wide variety of experiments. LCLS can image samples down to the size of atoms and see processes that occur in less than one tenth of a trillionth of a second! Consequently, LCLS is embarking on ground-breaking research not only in physics but also in chemistry, biology and various other fields. Research done at LCLS has allowed scientists to discover how DNA guards itself against damage from ultraviolet light and map the structure of an enzyme that is relevant to the African sleeping sickness disease, just to name a few of the things discovered at LCLS. Scientists from all over the world use the LCLS facility to carry out their research and add to the body of scientific knowledge. Science is a global field and can only progress with the collaboration of minds all around the world.



One of the experimental vacuum chambers in the Coherent X-ray Imaging (CXI) experimental hutch. Here, X-ray crystallography experiments have allowed scientists to image biological samples without damaging them because of the very short pulse duration.

The X-ray Correlation Spectroscopy (XCS) experimental hutch is used to carry out experiments that observe dynamical changes of large groups of atoms. The SLAC director, Chi-Chang Kao (far left) and LCLS director, Mike Dunne (far right) can be seen in this picture.

LCLS is currently undergoing an upgrade where LCLS-II will build from the success of LCLS. It will go from producing 120 X-ray pulses a second to 1 million pulses a second which will be 10 000 times brighter! This upgrade will allow scientists to perform experiments that are currently impossible enabling us to make discoveries that shall advance technology and our quality of life further and hopefully help produce new energy solutions. Thus, exciting times lie ahead of us in the field of X-ray free electron lasers – look out for more discoveries in the next few years!

Meriame Berboucha is a final year undergraduate student of Physics at Imperial College London. In the summer of 2016 she was the first international student to win an internship at the Linac Coherent Light Source, SLAC, California, USA.

Meriame explains her work at the end of her internship at LCLS, SLAC.

Look here!

Watch a short film about LCLS-II: *https://www.youtube.com/watch?v=t7jUZwhZdd0*

A European collaboration is building an XFEL: *http://www.xfel.eu*

Find out more about Meriame's career in Physics: *http://meriameberboucha.weebly.com*