UK X-ray FEL Facility

Overview

In this brief document we present the case for building a UK-based X-ray Free Electron Laser facility. This case is intended for submission as input to the UK Government consultation on the UK's scientific infrastructure. We strongly recommend that this action is taken, alongside a full engagement with the European XFEL project in Hamburg, so as to provide British science with vital access to the most advanced photon sources in the world. X-ray Free Electron Lasers (FELs) can generate X-ray pulses of a *hundred thousand times shorter* duration than those from a synchrotron whilst being a *billion times brighter*. The transformational impact of these light sources on science has already become apparent with the high profile and diverse scientific outputs already achieved by LCLS in Stanford since it switched on 5 years ago. The UK can no longer afford to remain on the side-lines as we are in danger of losing ground permanently across a very wide spectrum of X–ray science which will have impact on our competitiveness in advanced engineering, nanotechnology, biotechnology and pharmaceutical industrial sectors. We present here a plan for XFEL infrastructure that will mean the UK will operate as one of the continuing leaders in X-ray science for decades to come.

International Context

This proposal comes in the light of the obvious scientific success of LCLS in the USA and the growing momentum for X-ray FEL science around the world. The existing hard X-ray FELs are LCLS in the USA and Sacla in Japan. The Euro XFEL will become operational in 2017 and will be a world-leading international facility as it is the first high rep-rate hard X-ray FEL surpassing all existing machines in performance. A high repetition rate machine is also planned in the USA (i.e. LCLS II), and further national facilities for hard X-rays in Switzerland and Korea are also well on the path to completion. Soft X-ray facilities are operating in Italy and Germany, and one is being constructed in China. Currently there are no plans tabled for a UK-based facility of this sort and we think there is now a compelling case for such a machine on the grounds of the need for this scientific and technological capacity and capability.

Preliminary analysis shows that within the budget envelope likely to be available from the currently anticipated capital budget, a world class machine could be built which would equip the UK with a long term wold-leading capability. We can anticipate a broad photon energy range from 50 eV to 15 keV, X-ray pulse durations down to 3 fs and pulse energies at the milli-Joule level. The UK is well placed to design and build a machine with unique capability due to the exceptional quality of our accelerator and laser scientists working within STFC and at UK Universities. By optimising the design, a world-class capability can be created. This will attract users and investment from beyond the UK and also from important sectors beyond academia.

The plan to build a UK X-ray FEL is not intended to replace future deep involvement with Euro XFEL and further engagement with similar facilities. We see both as part of a viable long-term strategy to provide the light source infrastructure the UK will need for the coming decades. Moreover, there is strong evidence that a UK based facility will have direct economic and societal impact that goes well beyond the important science it will directly generate. We believe that this facility would be a huge boost to the UK's scientific infrastructure and international scientific prestige.

Key Features of a UK XFEL Facility

In the table below we highlight the likely specifications that we can anticipate from a machine costing within the budget envelope of £450 M. We also list below future up-grade options that could further enhance the capability of this facility.

UK XFEL Specification

Photon Energy Range	< 100 eV to >15 keV
Pulse bandwidth	~ 1 % SASE ~ 0.1% Self-Seeded SASE
Pulse Energy	> 10^{12} photons per pulse
Photon polarisation	linear to circular
Pulses per second	up to 400 per second or 100 per second in 4 FELs simultaneously
Pulse Duration	< 3 fs to 30 fs
Smallest focus	< 1 micron
Max intensity	~ 10^{19} Wcm^{-2}
Synchronisation to external laser	+/- 50 fs
Time stamping accuracy with external laser	< 10 fs
X-ray split and delay resolution	< 1 fs
Auxiliary synchronised sources	Tuneable THz (1 – 100 meV) Lasers (100 meV to 6 eV) High power femtosecond and nanosecond systems
Separate FELs (3 or 4) independently tuneable	SXR (0.1 – 2 keV) MXR (1.5 – 6 keV) HXR (5 – 15 keV)
End-stations	3 per FEL
Experiment-Hours Delivered per Year	15,000 – 20,000

By constructing this facility at the Harwell campus we will create unique opportunities for science and inter-facility collaboration with ISIS, Diamond and the CLF. For example, the combination of the CLF 20 PW up-grade and end-stations on the FEL accessible to these laser pulses will create a unique scientific opportunity un-matched anywhere in the world.

Future up-grades and enhancements might include:

- An enhanced higher rep-rate capability at lower photon energies
- Additional laser seeded VUV FEL (10 – 400 eV)
- An end station with access to 10 PW short-pulse and kJ-class nanosecond pulses from CLF upgrade
- An end station with access to a synchronised relativistic electron beam obtained from the Diamond synchrotron
- Two-pulse/ two-colour capability
- High power HHG beam lines for XUV pump-X-ray probe experiments
- Sub – 1 fs pulses
- Strong pulsed magnetic fields

Scientific Potential

X-ray Free Electron Lasers (FELs) provide a new science and technology capability. It has emerged in the last 5 years as the most important development in X-ray light sources in 40 years. The unique capabilities of these sources, to provide laser-like coherent X-rays of exceptional brightness and very short pulse duration, are already proving to be at the cutting edge of science. These light sources allow us for the first time to see inside matter and capture the *nanoscopic motions* that determine macroscopic properties and function.

The immediate impact of these facilities on science and technology is likely to be highest in the following broad areas:

Structural Dynamics

The ability to probe structure and dynamics at the fundamental scale (sub-nanometre/femtosecond) provided by X-ray FELs is going to have impact on, for example basic energy sciences (e.g. light harvesting technology), catalysis, research into strongly correlated systems (e.g. high T_c superconductors), nanotechnology devices (for photonic and analytical applications), structure of matter under extreme conditions (e.g. strongly coupled plasmas). This potential impact is reflected in major new investment into groups developing this science in the USA (SLAC) and Europe (CFEL and the Max-Planck Institute for Structure and Dynamics of Materials MPSD).

Nanoscale Imaging Science

X-ray FELs, due to their coherence, brightness and temporal structure, permit new avenues for imaging i.e. coherent diffraction imaging (CDI). CDI using X-ray FELs has the potential overcome the technical impasse encountered for imaging *non-periodic structures* and *non-crystallizable proteins.* Recently proof-of-concept results were reported from the LCLS facility in single shot imaging of biological systems and structure determination of the light harvesting protein in a nanocrystalline form. These are first steps that may lead to radical advances in the ability to image the functioning of sub-cellular structures in live biological systems. Moreover the potential to determine protein structure in samples that cannot be crystallized at all or only yield tiny nano-crystals is delivered by these facilities. A strong international effort is underway in this imaging technology led by groups in Europe and the USA.

These broad themes illustrate only some of the possibilities currently being opened by X-ray FELs. In the course of the next 10 years there will certainly be major breakthroughs not only in these areas, but no doubt in many others. It is highly likely that there will be a significant impact on future energy technology based on advanced chemical-, bio- and nano-technology, catalysis, drug discovery, biomedical imaging, high energy density plasma science etc.

For the UK XFEL we anticipate having available the following end-stations that will enable the research outlined above and in the next section:

End-Station	**FEL Photon Energy**
Ultrafast Science	SXR
Chemical Dynamics	SXR
Nano- bio- imaging	SXR
Time-resolved X-ray Spectroscopy	MXR
Coherent Diffractive Imaging	MXR
Non-linear X-ray Science	MXR
Serial Crystallography	HXR
High Energy Density	HXR
Hard X-ray Spectroscopy	HXR

Further end-stations may include those optimised for:

- Single molecule imaging
- Attosecond science
- Ultrafast magnetization dynamics
- Correlated electron materials
- Catalysis
- Imaging engineering structures in real time

Some Key Research Directions Enabled by the UK XFEL

We now highlight specific examples of the world leading research that the UK science community would be able to carry out with this facility. For all of them an X-ray FEL is essential and the capabilities of the planned machine would be excellently matched to their requirements.

Engineering Diffraction
Dr David Dye, Imperial College

"Britain's leading edge, high value-added industries rely on leading science to enable industrial innovation and competitiveness. For example, laser shock peening is a material surface treatment technique that is widely used to inhibit surface cracking and fatigue of, e.g. titanium parts used in aero jet engines. There a laser pulse around 10ns in duration is used to induce a shock wave in the material. The next generation of tools include femtosecond machining, pushing the timescales even further. Often, industrial process development has run ahead of the science, preceding an in-situ, time-resolved understanding of the materials mechanisms at work, which has meant that process optimisation has been empirical and slow. Understanding the dynamics of these processing techniques on relevant timescales will enable improved understanding and optimisation, leading to enhanced material, component and therefore design performance.

Understanding ultra-high rate deformation mechanisms can also be of considerable importance even for load regimes that are much slower; for example the balance of energy absorption between twinning and dislocations at a crack tip, or in the bulk in terms of strain heterogeneity. This is because, in low dislocation density materials, very often dislocations can travel at velocities similar to the local speed of sound.

A further example is combustion; the examination of chemical reactions occurring in fuel droplets travelling through shock wave fronts. It goes without saying that understanding combustion processes is critical to reducing NOx, SO2 etc production. XFEL experiments will not just be important in the femtosecond regime but at all timescales faster than those attainable by current in situ probes such as synchrotrons. These phenomena are critical to understanding materials performance limits, and hence to the prospects for making lighter, more efficient, more competitive jet engines that reduce emissions. These are also safety-critical systems, as in nuclear power generation, where failure cannot be tolerated.

This research will require X-ray energies relevant to engineering diffraction, >5keV and preferably higher (up to 25 keV), end stations appropriate for orientating and imaging samples under the ~10-500 micron beams, and short pulses with good time stamping and registration to the pump-probe optical lasers."

Time Domain Material Exploration
Prof Ian Robinson, University College London

"The UK-XFEL offers the exciting opportunity to explore phase diagrams in the time domain. Entirely new states of matter could be discovered in this way. Once these are know to exist, they could be stabilized by other methods, not unlike the way high-pressure phases can be 'adjusted' to ambient conditions today. There are already a few reports in the literature of "hidden phases" of matter which are metastable but

can be created by optical excitation. Lifetimes of nanoseconds to microseconds are typical, so their existence and time evolution can be recorded by optical pump X-ray probe methods. Closely related are displacive phase transitions between stable phases which can be driven optically, such as that recently reported in CdS from LCLS.

The best way to establish the phase diagram is by powder diffraction, for which sufficient powder averaging can be achieved by very small nanometre-sized grains, which provide sufficient signal from a single X-ray shot, but require a sufficient range of orientations. It is assumed that the sample will either be damaged by the X-ray beam and/or the optical excitation into the metastable state, so a way of feeding samples faster than the XFEL repetition rate will be devised. Various options will be developed and tested on conventional synchrotron sources, including thin films on membrane and liquid jets. The requirements on the UK-XFEL design would be for i) short enough X-ray wavelength to cover several Bragg peaks, for example 10keV ii) a sufficient number of X-rays per shot, for example 10^9, and iii) a repetition rate compatible with complete readout of an area detector, for example 1000Hz."

THz frequency Control of Solids and Discovery of Hidden Phases
Prof Andrea Cavalleri University of Oxford

"Mid infrared and THz frequency optical pulses can dynamically distort the lattice of solids, driving nonlinear lattice motions and sculpting new crystal structures with light. Such lattice control can reveal hidden phases, driving insulator metal transitions and even inducing superconductivity above the equilibrium transition temperature Tc. Strikingly, it has been shown that such lattice control in the cuprate $YBa_2Cu_3O_{6+x}$ can induce a transient phase with important features of the superconducting state up to room temperature. Pump probe measurements combining such THz excitation and x-ray probing at the LCLS have made it possible to partially understand the nature of these non-equilibrium states, for example revealing exotic phases in which charged stripes disappear in a virtually unchanged crystal lattice, not possible in equilibrium cuprate, or by reconstructing the lattice structure of the solid in the transient state.

This work in cuprate is only one example of a new generation of experiments in which the functionality of solids is controlled by light, unveiling the physical principles that may lead to a new generation of optoelectronic devices and exploring unknown regions of the free energy landscape of solids. The use of X-rays to study the microscopic texture of these hidden phases, for example by reconstructing optically induced unstable crystal structures with unexpected functionalities, may provide new inspiration for materials design and recreate these properties at equilibrium.

This research will require; (a) tuneable sources of THz radiation, using both lasers and an auxiliary accelerator, synchronized to the X-ray Free Electron Laser (b) X-rays covering edges from carbon (285 eV) to beyond that of iron (7130 eV), (c) hard X-rays beyond 10 keV for femtosecond crystallography."

Ultrafast Magnetization Dynamics
Prof Rob Hicken, University of Exeter

"The 'big data' revolution and cloud based computing of the coming decade demand new data storage solutions, and indeed, the consumer is already accustomed to relentless improvement in the capacity and speed of magnetic data storage devices. The UK is a major player in data storage, with about 30% of the world supply of hard disk recording heads being manufactured by Seagate Technology in Northern Ireland. The vitality and capability of the research base is essential in maintaining the UK's position in hard disk recording and attracting investment for new technologies such as magnetic random access memory (MRAM).

The challenges faced by hard disk recording today are formidable indeed. For many years increased storage density was achieved by a process of scaling, which has now reached hard physical limits. Within *the storage medium, reduced grain sizes lead to thermal instability, the so-called superparamagnetic limit, which necessitates the use of 'stiffer' media that can no longer be written by conventional recording heads. The industry is therefore moving to assisted recording methods, most immediately heat assisted magnetic recording (HAMR) and in the longer term microwave assisted magnetic recording (MAMR) or opto-magnetic recording in which angular momentum is transferred directly between a laser field and spin-polarized electrons. In the read channel, smaller giant magnetoresistance (GMR) sensors will operate with current bias that is sufficient to introduce parasitic spin transfer torque (STT) effects. New materials and architectures will be required to maximize GMR while suppressing STT. The underpinning processes within both the storage medium and transducers occur on femto and picosecond timescales and at deep nano length scales.*

The power of time resolved soft x-ray measurements in addressing these challenges has already been demonstrated. By tuning to core level transitions, element specific x-ray magnetic circular dichroism (XMCD) measurements reveal the internal magnetization dynamics of alloys and multilayers. For example, 100 fs x-ray pulses have been used at BESSY to identify a novel thermally induced toggle switching that occurs in ferrimagnetic GdFeCo alloys on timescales of about 1 ps, while time resolved x-ray microscopy has been used at the ALS in Berkeley to image STT driven magnetization reversal in a nano-element.

Looking forward, future progress requires x-ray sources that (i) have pulse durations ~10 fs, substantially shorter than the demagnetization time (~100 fs), (ii) energy that can be tuned to core level transitions that yield XMCD in both transition metal and rare earth elements (typically 500 – 3000 eV), (iii) can be synchronised with ultrafast lasers and microwave synthesizers, (iv) have fully tuneable polarization for the measurement of XMCD in ferromagnets and x-ray magnetic linear dichroism (XMLD) in antiferromagnets".

High-Pressure Phases and Transitions Accessed via Laser Compression
Prof Malcolm McMahon FRSE, University of Edinburgh

"Until recently, the traditional view of how matter behaved at extreme pressures was that all materials would trend towards high-symmetry, close-packed metallic phases. We now know the true behaviour to be completely different – and much more interesting. Under compression, interactions between the core electrons on neighbouring atoms emerge, resulting in extreme structural complexity. Even aluminium is predicted to undergo a transition to a complex incommensurate form above 3.2 TPa (32 megabars), and this exotic behaviour has called for a paradigm shift in the understanding of how high-density matter behaves.Dynamic compression methods, where extreme pressure-temperature states are created for several nanoseconds using high-power lasers, are now allowing us to access high-density states of matter previously inaccessible. Such timescales are perfectly matched to XFEL pulse lengths, and using the LCLS, we have shown it is both possible to obtain high-quality diffraction patterns from dynamically-compressed samples using a single x-ray pulse, and to observe phenomena not previously reported in static compression studies.

The potential of this method for accessing and studying high-density matter has been recognised by EPSRC and STFC, who have recently funded a high rep-rate, high-power laser at the Euroa XFEL. But a UK-FEL, providing 30fs pulses of hard x-rays (15 keV), and situated beside the CLF, one of the world's leading laser facilities, would allow us to conduct detailed diffraction and scattering studies of matter at conditions only otherwise found deep within planets and exoplanets. The shot rate at such a facility would represent a several order of magnitude increase over current techniques, and would open this field from the realm of discovery, to systematic study, exploration and exploitation."

High Energy Density Science and Shock Physics
Prof Justin Wark, University of Oxford

"Such is the power of XFELs that they can be focussed to small, micron-scale, spots, at ultra-high intensities. As a result, solid-density matter can, within a few femtoseconds, be heated to temperatures of

several million degrees - that is to say density and temperature conditions that exist half way to the centre of the sun. As X-rays have a relatively long penetration depth (compared with optical light), isochoric heating can occur (atoms cannot even move a lattice spacing during the FEL pulse), so that the density of the resultant plasma can be known exactly. In this manner, matter which otherwise only exists within stars, or in inertial confinement fusion experiments, can be made with exquisite control. X-ray FELS can not only create such matter, but can probe it by a variety of means, such as inducing x-ray fluorescence, or X-ray Thomson scattering. When combined with high power optical laser technology (for example, by siting the CLF at the end of the FEL, as suggested by Prof. McMahon) a whole variety of plasma conditions can be created and interrogated. In this way experiments on a UK FEL would add enormous impact to the burgeoning field of "Laboratory Astrophysics", a field in which physicists re-create, in miniature, astrophysically relevant experiments in the terrestrial environment. The UK has a high international reputation in this area, and a UK-FEL/CLF combination would be an absolutely unique feature, with optical lasers far more powerful than associated with any other X-ray FEL on the planet.

High Energy Density Science is an over-arching title that not only encompasses the study of dense plasmas, but also of solid state matter subject to (optical) laser shock-compression. Laser-driven compression, whether ramped (as mentioned above by Prof. McMahon) or in the shock regime, is often performed in uniaxial-strain geometry (i.e. a planar compression wave is formed, with the lateral extent of the compression being much larger than the propagation distance of the wave). This constrains the system to be uniaxial in total (elastic plus plastic) strain. As high normal stresses are applied to the sample, huge shear stresses build up, leading to plastic flow (and often phase transitions). The relaxation of shear stress, by homogeneous dislocation generation and motion and/or by deformation twinning is still poorly understood. Much of this lack of understanding arises as the processes are predicted to be fast - on the picosecond, but also because the deformation mechanism cannot be fully gleaned from recovery experiments - the defects tend to annihilate during the rarefaction wave. An X-ray FEL will allow, with 100-fsec X-ray diffraction, the elastic strain states of laser-shocked materials to be interrogated all the way up to 10Mbar. These sorts of experiments have direct relevance to the field of impact physics, defence related problems, and, at lower pressures, to the surface treatment of metals by laser peening - a technique used extensively in industry.

The prosecution of this research, which necessitates high repetition rate optical laser systems, will require careful coordination with the Central Laser Facility at the Rutherford Appleton Laboratory. At present, for all other FELs around the world, relatively small optical laser systems have been placed alongside the FEL, but here in the UK, given the proposed siting of the system, we have the unique opportunity to ensure that a significant capital investment in both the CLF, and a UK –FEL, could result in co-ordinated co-location.

Ultrafast Electronic Dynamics

Prof Jon Marangos, Imperial College London

"The motion of electrons following sudden photoexcitation is a ubiquitous first step in many phenomena in photochemistry, radiation biology and light harvesting. It precedes the subsequent coupled electronic and nuclear motion that then leads to charge transfer, biomolecular damage and chemical change. Due to the very rapid timescales of the primary electronic events this research requires a light source with pulses of a few femtosecond duration. Pump-probe measurements of electronic dynamics in gas and condensed phase systems are thus a ripe area for study with the UK XFEL. The methodology would utilise the methods of time-resolved X-ray spectroscopy to track the electronic excitation, hole dynamics and subsequent structural changes. Sudden excitation via a synchronised laser source or an initial X-ray pulse would be accompanied by a combination of probe methods such as X-ray absorption/emission techniques, X-ray induced electron spectroscopy and EXAFS/XANES as probes. Temporal resolutions using time-stamping techniques in laser pump- X-ray probe methods will allow temporal resolutions down to 10 fs and X-ray pump-probe methods to a few femtoseconds allowing the first moments in the excited electron dynamics to be probed.

This research will require (a) low bunch charge short pulse operation to generate few-femtosecond pulses, advanced-time-stamping and self-seeding, (b) X-rays covering edges from carbon (285 eV) to beyond that of iron (7130 eV), (c) end stations equipped to handle liquid jets as well as solid and gas phase targets."

Structural Dynamics of Chemical Reactions
Prof John Evans, University of Southampton

"Since the time constant intrinsic to the stretching of any chemical bond lies between ~10 and ~300 fs, this XFEL provides the prime technique for visualising reaction pathways. X-ray diffraction and spectroscopic methods will provide direct structural measures in time slices through a chemical conversion in crystalline and liquid/glassy materials, respectively. X-ray absorption, emission and inelastic scattering will afford correlated detail of electron transfers through the process. Valuable structure-function correlations can be derived using a synchrotron source for sub-second events (down to ~ 100 ps), but these studies must be 1000-10000 times faster to probe the primary steps bond-making and –breaking.
The basket of key problems contains molecular electronics (e.g. switching of molecular magnets or metal-insulator transitions in organic metals), biomolecular processes (e.g. photosynthesis, enzymic electron and atom transfers) and chemical catalysis. More than 90% of chemical manufacturing processes involve catalytic steps, and improving the efficiency of these conversions is essential for sustainability of fuels, pharmaceuticals and materials. Understanding the decision points in light, electrochemical and thermally driven reactions is key to effective catalyst design. Coupling the appropriate pump triggers with XFEL probes will provide that opportunity.
The energy range envisaged for the hard X-ray FEL is appropriate for diffraction measurements. The three FELs together provide coverage for X-ray spectroscopy of the Periodic Table from element 4 (Beryllium), with liquid and solid samples viable at the MXR and HXR sources. Temporal resolution of ~ 10 fs will allow investigation of fast photophysical and electron transfer processes and follow atoms transfer dynamically. The repetition rate (~ 400 Hz) closely matches sample replacement rates and this XFEL source can be used to high efficiency."

Hard X-ray Nanocrystals
Prof Jim Naismith FRS, St Andrews University

"Protein crystallography has revolutionised biology, it has led to effective treatments for HIV, new antibiotics, new vaccines (including for foot and mouth), several Nobel prizes and with the breakthrough in the structure of G-coupled protein receptors whole new families of medicines. Every pharmaceutical company and almost all biotechnology companies have in house structural biology. In the UK, the vibrancy of the Industrial linked structural biology community can be seen in the high demand for access to Diamond Light Source. The UK's leadership in this area has been enabled by the foresight of government and in recent years in partnership with the Wellcome Trust to invest in cutting edge facilities. Most recently the UK has committed to partner in the building of a Serial Femtosecond Crystallography station at the EU-XFEL (BBSRC and Wellcome) but most significantly Diamond Light Source (STFC and Wellcome) and in the past the Daresbury synchrotron (the first truly user facility in the world). The economic benefits to the UK can be seen in the new jobs created in the biotechnology sector, the inward investment by large pharmaceutical companies and the export of technology / know-how.
The health of the Industrial activity is underpinned by the academic community. In life sciences, the UK punches well above its weight (in terms of spend, population and total publications) in the numbers of highly cited papers and structural biology is regarded as one of the jewels in the UK's crown. The partnership between academic and industrial is strong in structural biology, particularly in protein crystallography and dates back to at least Dorothy Hodgkin. For protein crystallography XFEL offers a disruptive technology. Many of the most challenging problems in biomedicine involve proteins or viruses which do not give crystals suitable for examination on current sources. This is because roughly speaking the information content of a protein crystal is a function of its diffraction resolution, the higher the resolution the more value that can be obtained and thus translated into understanding. Putting more photons into a crystal (higher incident beam intensity or longer exposure) increases the resolution of the measurement, the triumph of third generation synchrotrons such as Diamond has in part come form their ability to put more photons in about a 1 second exposure. Due to signal to background issues, higher intensity works better than a longer exposure. Synchrotrons are however limited by a fundamental problem, X-rays ionise atoms and this destroys samples. Thus even were it possible to increase the synchrotron intensity by 100 fold, the output diffraction would remain limited by the X-ray dose delivered

to the sample. XFELs by delivering the photons in a very short duration pulse gets round this limitation because although the sample is destroyed, the atoms appear stationary to the pulse. The same principle underpins stroboscopic lighting which appears to produce freeze frame images of a moving object. Current best estimates of the time window are around 40 to 50 fs, thus photons delivered in this time frame are immune to the limitations of sample radiation damage. XFELs would allow increases of to 100 fold more photons incident upon the sample than currently possible. Early work from existing XFELs suggest this promise will hold true, structures have been reported from very small weakly diffracting crystals that do not give useful data with current technology and data have been recorded from crystals before they are destroyed. We can be confident that the technology will exist to extract information from these experiments. It is precisely determining structures from small weakly diffracting crystals that will generate the most reward for the UK (small crystals are likely for the most rewarding projects)"

Next Steps

A. Development of a strong science capability in the UK in these emerging fields by investment in the major European project Euro-XFEL to ensure adequate access for UK researchers.

B. Bringing together UK expertise in FEL technology and the FEL user community to commence the design of a UK based FEL facility which will have internationally competitive performance and features. Additionaly, support for the CLARA FEL test facility at Daresbury will develop the UK FEL technology skill base, lower the project risk, and ensure the delivery of an FEL facility.

C. Making provision for moving ahead in a timely fashion with the construction of a UK based FEL, to be operational in ~2021

Conclusion

A UK XFEL would ensure UK Science remains equipped with the most advanced tools for X-ray science. Past experience has shown that advanced X-ray sources are a key underpinning capability for a vast range of scientific activities; e.g. materials, catalysis, chemical dynamics, high T_c superconductors, high pressure and high energy density processes, structural biology and nanoscience. In order for UK researchers to remain at the forefront of a wide range of X-ray enabled science, it is essential that the UK advances its capability to the international standard in X-ray sources by taking this step. Moreover there are likely to be long term benefits that will underpin present and future industrial sectors.