UKERC

UKERC ENERGY RESEARCH ATLAS: NUCLEAR FUSION

Revised by Chris Warrick, Martin O'Brien & David Ward of CCFE, and Chris Nelson & Chris Edwards of STFC Rutherford Appleton Laboratory - November 2013

1. Overview

Return to Top

Characterisation of the Field

Fusion is the power source of the Sun and the goal of fusion research is to establish it as a viable option for providing for our future world energy needs. The particular strengths of fusion are 1) the enormous fuel resources, and hence its capability to provide many thousands of years of energy supply, 2) its intrinsic safety- due to very low amounts of fuel inside the power plant at any time, and that little or no long-lived radioactive waste is produced, 3) the extremely low levels of atmospheric emissions, with Zero carbon dioxide and a small amount of the inert gas helium produced. Although the plant components do become radioactive, they will be safe to conventionally recycle within 100 years.

Fusion is researched in many countries around the world and is a highly co-ordinated research area. The UK work is an integrated part of the EU effort, which in turn is increasingly co-ordinated with work worldwide. It should be noted that fusion research divides into two main areas Magnetic Confinement Fusion (MCF) and Inertial Confinement Fusion (ICF). These techniques are fundamentally different, although there are many areas of research e.g. Better reactor materials, that apply to both. MCF employs magnetic fields to contain the very hot fusion gas or plasma. There is also significant research into ICF – a newer field using laser pressure to implode solid pellets of fuel to initiate fusion.

The international nature of fusion research makes the UK landscape difficult to report clearly. Much of what is reported here is an international research programme of which the UK is part, with a role that varies in magnitude – from large (for JET, the main EU experiment) to relatively small (for ITER, the new global experiment under construction).

CCFE (Culham Centre for Fusion Energy) is the UK's Centre for fusion research. CCFE (formerly known as UKAEA Culham) is based at Culham Science Centre in Oxfordshire, and is owned and operated by the United Kingdom Atomic Energy Authority (UKAEA). It is internationally important as the location of JET, the main EU experiment and presently the world's largest MCF device.

CCFE contributes to the key areas of study in MCF research, and to Materials and reactor research. The work is part of a co-ordinated European programme led by the European Fusion Development Agreement (EFDA). This is focused on providing Europe's input to the next-step international fusion experiment, ITER (see below), and the demonstration power station that is envisaged to follow it, known as DEMO.

Research at CCFE includes:

- Experiments on the MAST spherical tokamak;
- Running JET as a facility for EU collaborators and participation in the JET research programme;
- A theory and modelling programme into key areas of plasma physics and predicting performance of future tokamaks such as ITER (see below);
- Materials and technology studies for ITER and other fusion power stations.

Fusion research at CCFE is funded jointly by EURATOM and by the EPSRC.

ITER (International Thermonuclear Experimental Reactor) is a global collaborative venture involving the EU, Japan, China, Russia, India, US and South Korea. It will be the world's largest Tokamak, twice the size of JET and approximately eight times the plasma volume. The concept was initiated in 1985, and the ITER agreement was signed in 2006. The project is funded and run by seven member entities — the European Union (EU), India, Japan, China, Russia, South Korea and the United States. The EU, as host party for ITER, is contributing 45% of the cost, with the other six parties contributing 9% each. The project has a 10 year construction phase until 2019 and a 20 year operational phase. The construction is estimated to cost 13 billion Euros.

In the **ICF** field, the NIF (National Ignition Facility) in the United States is primarily dedicated to achieving nuclear fusion by this method. Ignition has not yet been achieved there (Oct 2013), although impressive developments continue in technology and in science : in a recent breakthrough the amount of energy released through the fusion reaction exceeded the amount of energy being absorbed by the fuel - the first time this had been achieved at any fusion facility in the world. HIPER (the HIgh Power laser Energy Research facility) is planned to drive the transition from scientific proof of principle to a demonstration power plant, capable of delivering electricity to the grid. This project has progressed through Concept and into the Preparatory Phase, (which ran until April 2013). This latter Phase defined the future phasing strategy and addressed financial, legal and governance issues, in parallel with technical risk reduction, all of which would be needed to progress the Project. Prior to a decision to proceed further with HiPER construction, the ignition scheme must be experimentally validated[1] at full scale on an existing facility such as NIF or it's French equivalent Laser Mégajoule (LMJ).

[1] Physics scheme validation

Both MCF and ICF are equally important as part of the 'High level Pathway for UK Fusion for Energy' (see 20 Year vision for UK Fusion) and are addressed in this Landscape.

The RCUK has a Fusion Advisory Board (FAB) to advise EPSRC and STFC on UK fusion for energy research, training and participation in International Projects. This covers MCF and ICF.

Fusion made enormous progress following the oil crises in the 1970's. This led to the production of 16 MW of fusion power in JET, thousands of times higher than before. The decline of energy R&D budgets following the reduction of oil prices in the 1980's and 1990's prevented fusion from taking the next step up to the scale needed for a power plant. The new emphasis placed on clean energy has resulted in a renewed impetus and the collaborative international effort to move to a power station scale device ITER which is designed for 500MW of fusion power.

There have been many reviews of the Fusion field over the last 10 years. See page 12 of the 20 year vision linked above for a comprehensive list of reviews to 2010, and further references on page 5-7 of the recent EFDA Roadmap. Significant reviews are detailed below in rough chronological order to guide the researcher in the field.

The European Commission's 2008 review of Facilities[2] recommended concentrating on ITER construction and all the associated R & D and in parallel developing the concept for DEMO (Demonstration fusion reactor). In the decade following ITER completion, an Engineering design for DEMO should be finalised. It noted the underlying importance of HPC (High Performance Computing) facilities, and also of IFMIF (a materials test facility) and the CTF (a component testing facility). It also

[2] R&D Needs and Required Facilities for the Development of Fusion as an Energy Source: European Commission 2008

highlighted the continuing importance of JET, the Japanese facility JT60SA and the Czech based facility COMPASS (see section 6 for explanation of each of these five facilities).

In July 2009, as part of the RCUK Energy Programme, the Science and Technology Facilities Council (STFC) and the Engineering and Physical Sciences research Council (EPSRC) set up an influential project to address a series of interrelated fusion issues that affected both councils. In MCF the issues included funding levels for JET and the MAST upgrade. In ICF the focus was on the HIPER project and its role in the international pathway to inertial fusion as an energy source. Underpinning all of this was the need for a long term UK vision for fusion in the international context. To help with the development of this vision, an Expert Group, chaired by Professor Keith Burnett, was convened. The key points of the resulting new strategy, which has been approved by EPSRC and STFC Councils, are available along with the Expert Group's 20 Year vision for UK Fusion summary published in 2010.

The 2009 'Burnett' review is currently (November 2013) being carried out again by the RCUK Fusion Advisory Board as planned at the mid programme point (2013) under the chairmanship of Phil Sharman.

The conclusions from EFDA's Nov 2012 Roadmap were;

i. The biggest problem for Fusion is the heat exhaust, and a dedicated Divertor Tokamak Test (DTT) facility is needed.
ii. Acceleration of materials testing is required, and the possibility of starting an IFMIF facility should be assessed, even if with a reduced specification.
iii. Europe must involve Industry early in DEMO, so that they have the capability to build Fusion power stations afterwards.

There is a network activity (see section 7) funded by EPSRC to develop a more programmatic approach to IFE research and development (similar to that in MCF), and highlight where the UK is best placed to have major international impact.

The early work in Fusion led to the EU collaborative venture JET, still the world's largest fusion device located at Culham in the UK. JET is now operated by the Culham Centre for Fusion Energy (CCFE) carrying out an experimental programme co-ordinated through the European Fusion Development Agreement (EFDA) to maintain Fusion research while ITER is developed. Most experiments on JET are therefore now designed to improve the knowledge base – in terms of science and engineering – for ITER, the new larger, international fusion device being built in France.

The UK also operates its own smaller fusion device, MAST, at Culham which investigates the science and engineering viability of more compact fusion devices and other research. Small aspect ratio ('Spherical') tokamaks like the original START, and now MAST, have not had as much development but potentially offer a more compact, efficient and cost effective design than conventional tokamaks. The £30M stage 1 MAST upgrade, approved as part of the 2009 EPSRC review, is planned for completion in 2015. It will increase the pulse length, and trial a new divertor concept. Importantly, it's success will build the case for the Component Test Facility as a spherical tokamak is seen as an ideal design for the facility.

Research Challenges

The main research challenges in Fusion are different for the two technologies.

MCF

i) Achieving the extreme conditions needed for fusion (in terms of temperature and effective confinement of the plasma fuel)
ii) Developing materials suitable for use in this harsh environment
iii) Addressing the major technological challenges associated with large scale fusion power production.

The first issue is closest to resolution and the emphasis globally is shifting onto the materials and technology issues, including the power handling challenge outlined above. The UK capabilities in these areas are addressed in Section 2. However, maintaining steady Plasma[3] is still an issue for MCF fusion physics, regardless of the type of device (toroidal or spherical). In 2011 the IEA's Fusion Power Co-ordinating Committee (FPCC) – see Section 9, created a cross-cutting Steady State Operations Co-ordination group to ensure this area of MCF research was covered internationally.

ICF

i. The main challenge is to demonstrate ignition with sufficient energy gain to make IFE (Inertial Fusion Energy) commercially viable.

ii. Also challenging, is how to build a practical, working system which delivers targets reliably to the reaction point, and then removes spent fuel.

Challenges Common to MCF and ICF

There is also a power extraction issue with a fusion reactor i.e. how to successfully remove heat from the reaction chamber to drive a conventional steam turbine without interfering with the plasma (MCF) or the targets and driver beams (ICF). Note that the MCF heat exhaust issue is identified in EFDA's Nov 2012 Roadmap.

[3] Read on 6/10/13 on IEA webpage on Fusion: http://www.iea.org/topics/nuclearfissionandfusion/

2. Capabilities Assessment

Return to Top

The UK is traditionally strong in fusion research due to the experience gained hosting and operating JET, the EU collaborative project which is still the world's largest fusion device until ITER is completed.

The domestic UK magnetic fusion research programme at Culham is integrated into the wider EU programme, as well as having a strong UK university component. It is strong in the following areas:

1. Experimental MCF research notably on MAST. MAST is one of the foremost fusion research devices in Europe – and one of only a handful supported by some level of funding from EURATOM. Its upgrade will give a more powerful device that can answer key questions for ITER and a fusion components testing programme.

2. Theoretical fusion plasma physics.

3. Modelling (at Culham) and experiments in materials science (primarily in collaboration with University groups), an important part of the strategy to commercial fusion power.

The UK is expanding its capabilities in fusion technology, partly through designing specialist equipment for ITER. This is providing a basis for an expansion into the technology needed for a demonstration power station.

UK MCF capability

In recent years there has been significant strengthening of the relationship between CCFE/Culham and the UK university base which is training the next generation of fusion scientists and engineers. In order to provide the skills required to achieve the fusion Fast Track (see 20 Year vision for UK Fusion), this investment needs to be sustained. In 2010, Culham had a PhD student cohort of 42 students (for which they provided some funding) spread roughly between three areas: plasma and related physics (28); materials science (4); and engineering and technology (10). These students came from 16 different universities with half being based at Culham and the rest visiting for prolonged periods. There were also students within the broader EPSRC physical sciences portfolio working in areas related to fusion but not receiving funds from Culham.

As JET operator, Culham also has unrivalled hands-on experience of fusion technology which is an asset for the world fusion programme and will be important for the exploitation of ITER. Through the development of the spherical tokamak concept, Culham also has expertise in designing and building fusion facilities that is being used for the MAST upgrade.

UK ICF capability

The UK has long experience of building and operating high powered lasers: VULCAN and HELEN lasers at RAL[4] and AWE[5] respectively, and more recently has completed the construction of the £100M ORION laser at The Atomic Weapons Establishment (AWE). The ORION system will be one of the premier high-power, high-energy lasers in the world and can be used by the

[4] Rutherford Appleton Laboratory (RAL), STFC
[5] Atomic Weapons Establishment (AWE)

UK academic research community for multi high power laser research such as ICF studies.

Also, world class expertise has been built up at RAL in recent years in the key ICF areas of target fabrication and high efficiency/high rep rate lasers. In addition, the research programmes at RAL and UK universities have produced numerous high quality PhD graduates who have gone on to assume leadership roles in inertial fusion efforts around the world.

It is believed that the UK’s experience as detailed above provides a sound basis for UK leadership and involvement in collaborative inertial fusion projects.

There has historically been a lack of sufficiently trained personnel for the UK to solely develop the materials, engineering and technology required for a major fusion project. However, in recent years there has been significant teaching funding by Government to address this and provide trained personnel in Fusion areas. The HIPER Project is designed to pool European resources, and since the next phase of HIPER is technology development and risk reduction, Europe is well placed to make significant progress.

There is a network (see section 7) assessing UK capability, including science, technology and technology, both in academe and in industry. It has carried out a preliminary survey but has not publicised its findings yet.

Table 2: UK Capabilities

UK Capability	Area	Market potential
High	MCF • Fusion Experiments – JET, MAST • Basic Plasma Theory • Materials – Modelling plus some experimental aspects • Reactor Studies • Heating & Instrumentation systems	Large influence over the design of prototype power plant. Large potential market for power plants.
	ICF • High Efficiency/Hi Rep rate Lasers • Target fabrication at RAL & AWE • MEMS/Nanotechnology, associated metrology & design capability	Enormous (Many £B)
Medium	MCF • Computational Plasma Physics • Fusion Technology (area rapidly increasing in size)	• High • Very high for power stations

3. Basic and applied strategic research

Return to Top

Nuclear fusion has the potential to offer an almost limitless source of energy with minimal environmental impact. While the timeline for delivery is beyond the 2050 emission target, fusion is an attractive technology that needs to be developed as one of the possible methods of supplying huge projected growth in energy demand as emerging economies develop.

There are still great challenges to overcome before fusion becomes a viable source of energy for the future but continued funding must not only provide the facilities and research base necessary for progression but also the skilled scientists and engineers needed to continue to work in this area.

The RCUK Energy Programme supports a full range of energy research including Fusion to help the UK meet it's energy objectives and targets.

The UK Fusion Programme is largely centred around magnetic confinement fusion at CCFE, one of the world's centres for fusion research. They are receiving a six-year EPSRC grant (2010 - 2016) of total £163.4M for the continuation of the UK Magnetic Fusion Programme.

The Joint European Torus (JET), is still the largest and most powerful magnetic fusion device in the world, and is based at Culham. JET is a precursor to the next generation fusion facility "ITER", which is now being built in Cadarache, France.

There is an Msc in Fusion energy at The York Plasma Institute (University of York). Also, CCFE aim every year to have new PhD and MSc projects with several UK universities addressing plasma physics, materials science and fusion engineering associated with tokamaks.

There is an EPSRC CDT (Centre for Doctoral Training) called 'The Fusion Doctoral Training Network' (FDTN) which is led by York University (Plasma Institute) in collaboration with Durham, Liverpool, Manchester and Oxford universities together with CCFE and STFC. It integrates postgraduate training in fusion science and technology with related disciplines such as technological plasmas, and also gives access to MAST, JET, Central Laser Facility at RAL, High Performance Computing facilities and International fusion devices. The York Plasma Institute is also part of the Network of Energy Doctoral Training Centres, which connects all the Energy related Centres for Doctoral Training across the country.

EPSRC previously awarded 'Science & Innovation Awards' of £3 – 5M over 5 years to universities involved in strategically important areas that were at risk. They funded staff in research groups, with a particular focus on producing new research leaders, and required continuing commitment from the host organisation afterwards. These grants were received in 2006 by Warwick (£5M) and Queens University, Belfast (£3.2M); and in 2008 by Edinburgh, Heriot watt and Strathclyde. See individual entries in Table 3.2 for details.

Note that there is a lot of research connected with materials for Nuclear applications e.g. radiation damage etc. within the nuclear fission area, which also has application to fusion. Readers interested in this area are advised to also consult UKERC's Nuclear Fission Landscape.

Research in the following tables has been designated as primarily 'MCF' or 'ICF' or applicable to both 'MCF/ICF'. Each organisation/row has been given an overall label for guidance.

In Table 3.1, The fusion programme at Culham is funded on the basis of full economic costs, which includes all staff, equipment, overheads and accommodation costs. The annual funding includes UK host payments for JET. Excluded from these figures are projects in universities funded by separate EPSRC grants.

Table 3.2 below shows the universities involved in relevant research. There are also Industrial collaborators including Dunlop Aerospace, Industrial Tomography Systems plc, Morgan Advanced Materials and Technology, Rolls Royce, Schlumberger Cambridge Research Ltd.

The Research Council funding just covers the UK universities, but there are also Overseas Collaborators including; Arhus University, Denmark; Tokyo University; University of Michigan; General Atomics; Massachusetts Institute of Technology (M.I.T.)

Table 3.1: Research Funding

Funding Stream	Funding Agency	Description	Committed Funds	Period	Representative Annual Spend
EPSRC Energy	EPSRC	MCF/ICF To research new options for future energy supply including Fusion Research, Materials Engineering and Plasmas and Lasers	£460m on all energy related areas	As at April 2011	N/A
EPSRC: UK Magnetic Fusion	EPSRC	MCF Relates to 6-year programme at Culham Centre for Fusion Energy (CCFE), to continue UK Magnetic Fusion Programme. Funds: 1. JET 2. Mast Upgrade 3. MAST experiments 4. Improving materials 5. Input to ITER	£163.4m	2010-2016	£27.3m

Funding Stream	Funding Agency	Description	Committed Funds	Period	Representative Annual Spend
EPSRC: Plasmas and Lasers	EPSRC	MCF/ICF This research area covers work into high temperature and high density plasmas either magnetically confined or produced by high power lasers. It covers the development of novel laser systems, laser physics and the understanding of lasing mechanisms	Plasma and Laser grants totalling £44.5M as of April 11, of which relevant energy grants are 24.2%	On-going	N/A
EPSRC: Materials Engineering	EPSRC	MCF/ICF Major Research Investments include; Materials for Fusion and Fission Power	Materials and Engineering grants totalling £48.7M as of April 11, of which energy related grants are 19.2%	On-going	N/A
EU Framework Programme	EU	MCF/ICF EU Research in Fusion	€900M	For FP7 (2007 – 11)	€225M for the whole EU programme of which about €55M is spent in the UK

Table 3.2: Key Research Providers

Name	Description	Sub-topics covered	No of staff	Field
University of Bristol	School of Physics	MCF/ICF • Boron Arsenide -Huge thermal neutron capture cross-section -Tremendous rad hardness		Physics Metallurgy and Materials
	Astrophysics group	MCF/ICF • Collaborations with the research group at CCFE on fusion plasma physics	1 academic	
University of Cambridge	Department of Materials Science & Metallurgy Phase transformations group	MCF/ICF • Understanding microstructure and behaviour of materials proposed for structural components in fusion power plants; vanadium and tungsten, iron and iron chrome binaries, also after irradiation	1 academic	Metallurgy and Materials Physics Mechanical, Aeronautical and Manufacturing Engineering
	Cambridge Nuclear Energy Centre	MCF/ICF • Radiation Damage and new materials		
	Department of Engineering	MCF/ICF • Modelling of materials for nuclear plant	1 academic	
Cardiff University	Department of Social Science	MCF/ICF • Making Sense of Fusion: Learning and Reasoning About an Energy Technology	1 academic	Sociology
CCFE (Culham Centre for Fusion Energy)	UK's centre for fusion research	MCF • See description of research in section 1, and research facilities in section 6	180 scientists and engineers working on the EPSRC programme	Physics
Cranfield University	School of Engineering	MCF/ICF • Investigation of Richtmyer-Meshkov instability (RMI). Applicable to a broad range of applications in science and engineering, including inertial confinement fusion (ICF)		Mechanical, Aeronautical and Manufacturing Engineering

Name	Description	Sub-topics covered	No of staff	Field
	School of Applied Sciences Manufacturing and Materials Department	MCF/ICF • Joining of dissimilar metallic materials (iron-aluminium, titanium-stainless steel and nitinol-stainless steel) for advanced structural applications.	1 academic	
Durham University	Centre for Advanced Instrumentation	MCF • Fusion Diagnostics for MCF • Hardware-accelerated computer simulation • interpretation of fast ion diagnostics. • Member of FDTN (see introductory text of section 3)	1^{+} academic	Physics
University of Edinburgh	Edinburgh Parallel Computing Centre, and School of Physics	MCF • Providing computational resources in support of ITER, and turbulence research. Note Nu-FuSE consortium involving six countries (France, Germany, Japan,Russia, UK and USA). • Novel Asynchronous Algorithms and Software for Large Sparse Systems (linked with Hull, Leeds, Manchester and Strathclyde universities) • Modelling plasmas, the plasma edge and reactor materials. Also training of young experienced fusion scientists. • Numerical Algorithms and software for HPC (EPSRC Science and Innovation award 2008 – 2013) with Heriot-Watt and Strathclyde universities.	1 academic	Computer science and Informatics
Heriot-Watt University	School of Engineering and Physical Sciences	MCF/ICF • Large scale Coating carbon tiles with diamond to produce superior plasma-facing wall	2 academics	Physics

Name	Description	Sub-topics covered	No of staff	Field
		materials.		
	Institute of Photonics and Quantum Sciences	MCF/ICF • Numerical Algorithms and software for HPC (EPSRC Science and Innovation award 2008 – 2013) with Edinburgh and Strathclyde universities.		
University of Huddersfield	School of Computing and Engineering	MCF/ICF • In-Situ TEM Studies of Ion-Irradiated Materials • Visualisation & Metering Technology for Multi-phase Flows	2 academics	Metallurgy and materials
University of Hull	School of Engineering	MCF/ICF • Novel Asynchronous Algorithms and Software, for Large Sparse Systems, applies to Nuclear Fusion Systems (linked with Edinburgh, Leeds, Manchester and Strathclyde universities)	1 academic	Computer Science and Informatics
Imperial College London	Department of Physics (the Blackett Laboratory), Plasma Physics Group	MCF/ICF 'The group continues to engage in both ICF and MCF research'. • Experimental investigations, and modelling on electron transport and shock propagation key to the development of laser driven particle and radiation sources in general and ICF in particular. • study of transient, high energy density plasmas • HIPER & Fast Ignition research • Tokamak Research	9 academic staff 20 Researchers	Physics
	Department of Mechanical Engineering	MCF/ICF • Imperial leads Centre for Doctoral Training in Non-Destructive Evaluation – inc fusion reactors	3 Centre Directors	Mechanical, Aeronautical and Manufacturing Engineering

Name	Description	Sub-topics covered	No of staff	Field
	Department of Materials	MCF/ICF • Predictive Modelling of Mechanical Properties of Materials for Fusion Power Plants	1 academic	Metallurgy and Materials
	Department of Chemical Engineering	MCF/ICF • Sonoluminescence	1 academic	Chemical Engineering
Lancaster University	School of Physics Accelerator physics group	MCF/ICF • WORKSHOP: Plasmas, Computation and Mathematics 2009	1 academic	Physics
University of Leeds	School of Computing	MCF/ICF • Novel Asynchronous Algorithms and Software for Large Sparse Systems Systems (linked with Edinburgh, Hull, Manchester and Strathclyde universities)	1 academic	Computer Science
University of Liverpool	Engineering	MCF/ICF • Supporting Materials research for Fusion & Fission power (co-investigators)		Mechanical, Aeronautical and Manufacturing Engineering
	Electrical Engineering and Electronics	Member of FDTN (see introduction to section 3)		Electrical and Electronic Engineering
Loughborough University	Department of Materials (Previously Institute of Polymer Technology and Materials Engineering)	MCF/ICF • NETWORK: Grain Boundary Engineering • • Material Systems for Extreme Environments • • Development of Reduced Activation Ferritic Steels for Fusion Applications	2 academics	Metallurgy and Materials
University of Manchester	Department of Computer Science	MCF/ICF • Novel Asynchronous Algorithms and Software	2 academics	Mechanical Engineering Physics

Name	Description	Sub-topics covered	No of staff	Field
	Department of Mechanical, Aerospace and Civil Engineering	for Large Sparse Systems (linked with Edinburgh, Hull, Leeds and Strathclyde universities) • Member of FDTN (see section 3 introduction)		Computing science
University of Oxford	Materials	MCF/ICF • Materials for Fusion & Fission Power Group • Oxide Dispersion Strengthened alloys are a relatively new class of steels that are expected to play an important role as structural materials in future nuclear reactors • Study of radiation damage by heavy ions • Study of dense plasmas: important in laser-fusion pellets and solids heated to plasma temperatures during laser ablation	12 academics 4 researchers plus students	Metallurgy and Materials Mechanical, Aeronautical and Manufacturing Engineering Physics
	Engineering Science	MCF/ICF • material systems will need to be developed that can deliver the required performance at much higher temperatures than at present •	3 academic 2 researchers	
	Physics	MCF/ICF • Computer Simulation of laser plasmas • Physics of ICF/Ignition • Pedestal/Plasma edge effects • Novel Sensors for fusion research		
Queen Mary, University of London	Department of Physics and Astronomy	MCF/ICF • Molecular Dynamics Simulation code influence materials for future fusion reactors	1 academic	Physics

Name	Description	Sub-topics covered	No of staff	Field
Queen's University of Belfast	Centre for Plasma Physics (CPP)	MCF/ICF • Funded 2006 -2012 to form a coherent, critical-mass research group of nine academics with strength in experimental, theoretical and computational plasma	9 academics	Physics
University of Sheffield Department of Applied Mathematics	Solar Physics and Space Plasma Research Centre	MCF/ICF • Statistical Formulation of Intermittency in Magnetized Plasmas	1 academic	Applied Mathematics
STFC (Science & Technology Facilities Council)	Government Civil Science Research Laboratory	MCF/ICF • Investigation of tungsten and its alloys under high radiation fluxes and thermal shock for novel nuclear applications. • The CCPP Network in Computational Plasma Physics • Supporting partner in Plasma Physics HEC Consortia carrying out Software development and simulations • Supporting partner for SUSSP68 International Summer School in Laser-Plasma Interactions and Applications	4 academics (plus recent significant work on the HiPER preparatory phase)	Physics Computer Science and Informatics Mathematics

Name	Description	Sub-topics covered	No of staff	Field
		ICF • Research involving a comprehensive programme of experimental investigations, , designed to address questions on electron transport and shock propagation of fundamental importance to the development of laser driven particle and radiation sources in general and ICF in particular.	20	
	Centre for Advanced Lasers and Technology Applications (CALTA)	ICF • Established to develop the applications of High Power Lasers, e.g. High Efficiency / Hi rep rate lasers. Has won competitive bids for supplying £13M total of laser systems		Physics
	Uses the services of Spin-out company SciTech Precision	Production of micro Laser targets	6	Physics
University of Strathclyde	School of Physics, Plasmas Division	MCF/ICF • Beam driven instabilities in magnetized plasmas • Multi-Petawatt Laser Plasma Interactions • Novel Asynchronous Algorithms and Software for Large Sparse Systems (linked with Edinburgh, Hull, Leeds, Manchester and Strathclyde universities) • High End Computing HEC Consortia • SUSSP68 2011 International Summer School in Laser-Plasma Interactions and Applications • Numerical Algorithms and software for HPC (EPSRC Science and Innovation award 2008 – 2013) with Edinburgh and Heriot-Watt universities.	4 academics	Physics Electrical and Electronic Engineering

Name	Description	Sub-topics covered	No of staff	Field
	Electronic and Electrical Engineering	MCF/ICF • novel sensors to monitor and control experimental fusion reactor operation • Integrated Energy Initiative: Includes Nuclear Engineering. Also involves universities St Andrews, Manchester, Edinburgh		
	Scottish Centre for the Application of Plasma-based Accelerators (SCAPA)	MCF/ICF • Research incl. materials under extreme conditions as encountered in fission and fusion reactors (ITER, HiPER)		
University College London	Physics and Astronomy Materials modelling group Chemistry London Centre for Nanotechnology	MCF/ICF • Material selection for Nuclear Plants The common technique of Molecular Dynamics will help us to estimate the conditions under which we can expect surface melting at the first walls of fusion power plants and to suggest methods that will prevent surface melting occurring • Putting next generation fusion materials on the fast track • One proposal intends to coat carbon tiles with diamond on a large scale, in order to lower the erosion rates, dust formation, and tritium absorption, by using the unique properties of diamond. • Simulation Radiation Damage, and He Diffusion in apatite materials • Defect dynamics of materials, H2 Fusion power plants	2+ academics	Physics Chemistry Metallurgy and Materials
Swansea	Physics	MCF/ICF	1 academic	Physics

Name	Description	Sub-topics covered	No of staff	Field
University		• Theory Ionization of Atomic Hydrogen by Low Energy Antiprotons		
University of Warwick: Department of Physics	CFSA: Centre for Fusion Space and Astrophysics. Focused on plasma physics applied to the magnetic and inertial fusion power, etc The Centre has a strong record of joint work with the UK fusion research programmes, and has a longstanding collaboration with the fusion plasma theory group at CCFE	MCF/ICF • Fusion Plasma Physics • inertial fusion energy • Multiscale Modelling of Magnetised Plasma Turbulence • Quantifying, modelling and interpreting edge plasma turbulence in tokamak and stellarator fusion experiments • the physics of a burning plasma • The CCPP Network in Computational Plasma Physics • Plasma Physics HEC Consortia	6 academics	Physics Computing and Informatics
York Plasma Institute	University of York, Department of Physics /EPSRC collaboration	MCF/ICF • Many general areas of ICF and MCF Research • Theory of Explosive Plasma Instabilities • Member of FDTN (see section 3 Introduction)	12 academics 8 researchers	Physics

4. Applied research

Return to Top

All of the basic UK fusion research is outlined in section 3 - it is a mix of basic and applied research. The new machine, ITER, will move increasingly towards demonstration at the industrial scale.

5. Development and Demonstration Funding

Return to Top

All of fusion R&D is described in section 3; however, almost all of it is devoted to developing and demonstrating the feasibility of fusion power. As yet there are no demonstration plants, although there is increasing activity in the Conceptual Design of a Demonstration Power Plant in both MCF and ICF, partly to guide the near term research agenda.

6. Research Facilities and other Assets

Return to Top

The main research facilities in the UK are the European JET experiment, and the MAST facility, which are both located at CCFE.

In the future, UK researchers will make use of the international facilities currently (November 2013) being constructed or planned:

- ITER will become the dominant international fusion research facility, and JET will be wound down. ITER is being constructed in Cadarache in the South of France – with CCFE designing some key systems for the new machine and encouraging UK industry to bid for contracts.
- An International Fusion Materials Irradiation Facility, IFMIF (see table below), is being planned.
- Many Researchers also think there is a need for a Component Testing Facility (CTF) but there is not international agreement on this.
- HIPER (the HIgh Power laser Energy Research facility) is planned to drive the transition from scientific proof of principle to a demonstration power plant, capable of delivering electricity to the grid. This project has progressed through Concept and into the Preparatory Phase, (which ran until April 2013).

See Section 1 for further information about international activities.

Table 6.1: Research Facilities (UK-based and then International)

Name	Description	Type of asset	Number of Staff	Annual Operating Budget
CCFE (Culham Centre for Fusion Energy)	UK's national laboratory for magnetic fusion research. CCFE contributes to the key areas of study in MCF research. Activities at CCFE include: • Experiments on the MAST spherical tokamak; • Participation in the JET research programme; • A theory and modelling programme which studies key areas of plasma physics and predicts performance of future tokamaks such as ITER; • Studies of the materials and technology needed in ITER and fusion power stations. • COMPASS - Small Tokamak previously run at CCFE was transferred to Prague's Institute of Plasma Physics (IPP) in 2007	Research Lab	Approx. 950 staff and agency workers	
MAST (Mega Amp Spherical Tokamak)	UK research machine located at the CCFE – MAST is currently (November 2013) undergoing a ~£30M upgrade	4m diameter 1.3MA Spherical Tokamak	See above	
JET (Joint European Torus)	JET is the main EU fusion experiment. It is located at the CCFE and primarily funded through the EU Framework Programme. It is operated by CCFE on behalf of its EURATOM partners.	Major Research Facility 6m diameter, 5MA Tokamak	See above, plus ~350 European scientist visitors per annum	
ORION	Laser system at Atomic Weapons Establishment (AWE), Aldermaston. Commissioned 2013 Used for high energy density physics. Also Suitable for ICF studies Academic access form	Target chamber with 12 short pulse neodymium glass lasers 500J each	Six weeks per year beam time available to community	

Name	Description	Type of asset	Number of Staff	Annual Operating Budget
ITER (International Thermonuclear Experimental Reactor)	Global collaborative venture based in Cadarache in Southern France. Expected to be completed in 2019	**International Research facility** 19m Diameter Tokamak with Plasma volume of 840 cubic metres	42 hectare site. Estimated construction Cost €13 Billion	
JT-60SA	Joint Euro/Japan Fusion experiment being built in Nsaka. First plasma expected 2019. 'Satellite tokamak' as part of Broader Approach	**International Research facility** Superconducting Tokamak. Major radius half that of ITER	Upgrade of previous JT60 Tokamak at Japan's Naka Fusion Institute	
IFMIF (International Fusion Materials Irradiation Facility)	To test materials for a fusion reactor. The IFMIF, is *planned* by Japan, the European Union, the United States, and Russia, and managed by the International Energy Agency	**International Research facility** which would use particle accelerator-based neutron source to produce a large neutron flux from a liquid lithium loop, in a suitable quantity and time period to test the long-term behaviour of materials under conditions similar to those expected at the inner wall of a fusion reactor.	Part of the Broader Approach that Japan and the European Union formally launched in 2007. IFMIF is coordinated from Rokkasho, in northern Japan.	

7. Networks

Return to Top

Fusion is pursued as an international research venture with fusion laboratories in many countries worldwide.

The EU programme is co-ordinated under EFDA – exploiting JET but also co-ordinating other areas of European fusion research. Europe also has an agency (Fusion for Energy or "F4E") to procure equipment for ITER and fund R&D needed for specialist components before these can be procured.

Wider networks exist through formal agreements on ITER, the Broader Approach (an EU-Japan international agreement designed to further the goals of fusion power) and agreements through the IEA and IAEA.

Table 7.1 Networks

Network	Established	Description	Membership	Activities
FUSENET	2010	European Fusion Education Network The Fusenet Association is an independent legal entity that provides a platform for the coordination of European fusion education activities, the initiation, development and implementation of new EU-wide actions, and for the exchange and dissemination of fusion education information. The association is open to all European organizations that are active in the field of fusion education and research.	Universities, Research institutes and Industrial companies	Activities of FUSENET, in which industry can participate, collaborate, sponsor, advise or take interest in include; • Internships for students in industry • Research collaboration with industry for PhD students • Fusenet supports joint educational activities, such as summer schools and workshops • Fusenet partners share joint materials and set up hands-on experiments for students • Outreach and posting news on its activities and collaborations on the FUSENET website. • FUSENET has established EU-wide ambitious criteria for the award of Fusion Science and Technology Master & PhD certificates.

Network	Established	Description	Membership	Activities
CCPP	2007	Collaborative Computational Plasma Physics Aims to pool the collective expertise across all plasma physics areas including fusion power Also to develop core plasma physics simulation codes, and training packages, for UK science. The CCP includes staff from UK universities, UKAEA, Culham, RAL and AWE. The exchange of ideas, algorithms and codes between the laboratory plasma community and space and astrophysics community is planned to lead to a suite of core plasma simulation codes, documented and maintained within the UK which will benefit both research and PhD/PDRA training programmes.	30 UK academics from a range of Universities and institutes Members	Conference and workshops
Energy CDT Network	Active 2013	Network representing 13 EPSRC funded CDTs specialising in research/training in Energy –the Fusion CDT is a member of this network.	EPSRC CDTs	Provides an environment for UK Energy researchers to share expertise, network and access training opportunities.

Network	Established	Description	Membership	Activities
The UK Inertial Fusion Energy Network	Funded from 1/11/2013	A network to develop proposals for a more programmatic approach to IFE research and development, involving academe and industry , and also identifying where the UK is best placed to have major international impact and roles. • Also develop strategies for IFE based on future funding scenarios and scientific drivers • Also highlight benefits to industry e.g. by partnering with national laboratories to access and commercialise cutting edge technologies.	Open to all members of the UK's scientific and industrial communities with an interest in inertial fusion and supporting technologies	• technical and scientific workshops • large scale community meetings • community building and outreach activities that identify opportunities for cross-disciplinary collaboration (for example with MCF, Generation IV fission and materials research • discussion of the short, intermediate and long term goals and potential leadership of IFE activities in the UK

8. UK Participation in EU Framework Programmes

Return to Top

Much fusion research is co-ordinated at the EU level and is supported financially through the EU EURATOM Framework Programme. This supports JET and also provides additional funding of the domestic UK programme.

EU Framework funding in the area of nuclear research is covered separately as the EURATOM programme to the rest of EU funded activities. It was originally ring-fenced given the need to take forward essential nuclear research for safety etc but recognised that the topic was one that consensus amongst the EU nations was difficult to achieve. For FP6 the total funding was 1.3 Billion Euro with 824mEuro for the fusion programme. The fusion funding supports domestic research programmes in member countries, plus the JET facility in Oxfordshire which is the EU's leading facility and also preparation for ITER. At present the majority of MCF work carried out in the UK is funded from Europe as the UK hosts JET.

The FP7 budget for nuclear was €2.75 billion to be spent between 2007 and 2011.[6] In FP7 Euratom there were two associated specific programmes, one of which *indirect actions* included fusion energy as opposed to the 'direct actions' which are concerned with non fusion nuclear matters and are carried out at the Commission's Joint Research Centre (JRC).

Euratom indirect actions are managed by the Commission's Directorate-General for Research (DG RTD). The specific programmes allocate €1947M to fusion energy research, of which €900M is allocated to FP7 grants in MCF/ICF as opposed to institute funding (see table 3.2).

- [6] FP7 Nuclear Funding

Table 8.1: EU Framework Programme Participation

Project	Objectives	Action Line	Type of Action	Uk Participants	Co-Ordinator And Partners	Total Funding	EU Funding	Duration	Annual Spend
ADAS-EU	Extension of the ADAS (Atomic Data and Analysis Structure) Project - Provision of derived atomic/molecular data for plasma models. - Supports using atomic data in plasma diagnostics and modelling at fusion laboratories - Management of databases of relevant fundamental data - Unified system with common code and data assembled, organised, verified and archived centrally. - Will improve analysis of existing fusion experiments and prepare for ITER.	FP7-EURATOM-FUSION	Supporting Actions	University of Strathclyde	University of Strathclyde UK	€1.0 M	€900K	2009-01-01 to 2013-09-30 57 months	€210K

Project	Objectives	Action Line	Type of Action	Uk Participants	Co-Ordinator And Partners	Total Funding	EU Funding	Duration	Annual Spend
HIPER	Preparatory study of HPER, a multi-national European Inertial Confinement Fusion (ICF) laser facility	FP7-INFRASTRUCTURES	Integrating activities / preparatory phase	STFC	STFC UK 19 Partners	€12M (including €5M from STFC and €2.4M from Czech plus in-kind contributions	€3M	2008-04-28 to 2013-04-27 60 months	€600 K
STRUCMAGFAST The Physics and Applications of Magnetic Guiding of Fast Electrons through Structured Targets	Development of a numerical tool to study physics of the multi-ps regime, and apply to Fast Ignition inertial fusion and other high energy density physics applications.	FP7-IDEAS-ERC	ERC Starting Grant	STFC	STFC	€576K	€576K	2012-10-01 to 2016-09-30 48 months	€288 K
FEMAS-CA Fusion energy materials science coordination action	To create a European research environment in which fusion materials science for the realization of fusion power can be carried out with optimum effect.	FP7-EURATOM-FUSION	Coordination action	Loughborough University	Max Planck Gesellschaft zur Foerderung Der Wissenschaften E.V.	€3.2M	€2.1M	2008-10-01 to 2011-09-30 36 months	

Project	Objectives	Action Line	Type of Action	Uk Participants	Co-Ordinator And Partners	Total Funding	EU Funding	Duration	Annual Spend
FUSENET The European fusion education network	To establish a European Fusion Education Network for education in fusion science and technology. From secondary school level through to PhD. Leading to strong links between fusion institutes and higher education institutes.	FP7-EURATOM-FUSION	Coordination actions	The University of Warwick Queen's University Belfast UKAEA Cranfield University	Technische Universiteit Eindhoven	€2.5M	€1.8M	2008-10-01 to 2013-09-30	
FUTTA Fusion Technology Transfer Action	EFDA drives the development of technology that will be central to fusion power, namely plasma physics, materials and diagnostics. -To capture, record and publicise the successes from Technology Transfer by EFDA. -To increase the amount of Technology Transfer from EFDA Associates to industry and society in general. -To create a Technology Transfer capability dedicated to EFDA activities.	FP7-EURATOM-FUSION	Supporting Actions	ESA (of which the UK is a member)	ESA	€306K	€250K	2013-07-01 to 2015-06-30	

9. International Initiatives

Return to Top

As already mentioned, fusion research is strongly co-ordinated at the EU level by EFDA – with additional direct collaborations between national laboratories. The clearest example of the collaboration is the JET facility (see section 6).

Worldwide collaboration on the ITER Project (see section 6) sanctioned by the ITER agreement is very strong and is also supported by the International Tokamak Physics Activity (ITPA) and the EU Joint Undertaking.

The Joint Undertaking (between EU member states plus Switzerland) for ITER and the Development of Fusion Energy was created in 2007 for a period of 35 years. The objectives of the Joint Undertaking are to provide Euratom's contribution to the ITER International Fusion Energy Organization and to "Broader Approach" activities with Japan for the rapid realisation of fusion energy, and to prepare and co-ordinate a programme of activities in preparation for the construction of a demonstration fusion reactor (DEMO) and related facilities including the International Fusion Materials Irradiation Facility (IFMIF).

Further international collaboration is carried out under IEA Multilateral Technology Initiatives (formerly known as Implementing Agreements). There are 8 such initiatives that the UK is involved in (through CCFE, as detailed below).

Table 9.1: International Activities

Name	Type	Description	UK Contact Point
EFDA European Fusion Development Agreement	EU wide co-ordination agreement	Part of Euratom Programme of the European Commission. Co-ordinates fusion research in the EU, including the running of JET. UK participants are CCFE plus Universities.	
JOINT UNDERTAKING for ITER and the Development of Fusion Energy	International Collaborative Agreement	The Joint Undertaking provides Euratom's contribution to the ITER International Fusion Energy Organization and to "Broader Approach" activities with Japan to realise fusion energy. Also to prepare for a demonstration fusion reactor (DEMO) and related facilities including the International Fusion Materials Irradiation Facility (IFMIF).	

Name	Type	Description	UK Contact Point
ITPA International Tokamak Physics Activity	Collaborative research Programme	Originally under IAEA (Inception 2001), now under auspices of ITER (from 2008). Provides a framework for internationally coordinated fusion research activities. feeding into ITER Programme. Achieved a broad physics basis essential for ITER design and fusion research generally. Participants are the Members of ITER.	
IEA Fusion Power Co-ordinating Committee (FPCC)	International Co-ordinating Committee	Co-ordinates the IEA activities on fusion. Promotes international co-operation to realise Fusion power. Provides a platform for stakeholders to share results of fusion activities worldwide	
IEA International Energy Agency	Multilateral Technology Initiatives	List of Fusion Power Technology Agreements; • Co-operation on Tokamak Programmes • Environmental, Safety and Economic Aspects of Fusion Power • Fusion Materials • Nuclear Technology of Fusion Reactors • Plasma Wall Interaction in TEXTOR • Reversed Field Pinches • Spherical Tori • Stellarator-Heliotron Concept	Chris Warrick
IAEA International Atomic Energy Agency	International Agency	Cooperative agreement exists between IAEA and ITER to exchange research, and to organise meetings and conferences, training and publications together. Also aims to increase International cooperation and support on science and technology for fusion power. Publishes 'Nuclear Fusion'. Organises biannual 'Fusion Energy Conference' UK participant is CCFE.	
NEA (Nuclear Energy Agency)	International Agency	Part of OECD. Maintains database of nuclear data, codes and standards.	

Name	Type	Description	UK Contact Point
	MOU (Memorandum Of Understanding)	Between STFC, AWE, Lawrence Livermore National Laboratory (LLNL). To collaborate on ICF physics and technology press link	Chris Edwards
	MOU	Between the Japan Society for the Promotion of Science (JSPS) and STFC. Joint development of IFE physics. December 2008	Peter Norreys