THE ROYAL SOCIETY

Faster Fusion: New Ideas

Summarise your research simply in one sentence/ one brief paragraph. (This should be written for **non-scientists** and will be used as a summary for the committee).

Fusion power has the potential for abundant carbon-free energy but its realisation has always seemed decades ahead. Two developments could change this. High Temperature Superconductors (HTS) offer higher magnetic fields, and Spherical Tokamaks offer higher efficiency, together leading to smaller tokamaks and faster, cheaper development.

Summarise why you think this topic will make a good and interesting exhibit for the public and secondary school students.

Fusion is a highly relevant and emotive subject – relating to energy/environment and with varied science attractive to a broad range of people. Fusion features in the National Curriculum GCSE/A-level syllabi and is an excellent demonstration of the uses and implications of science as it brings together simple GCSE concepts and multiple disciplines to solve a real and pressing problem. The whole world needs an affordable, safe, carbon-free energy source. Fusion is one option.

The JET tokamak, Oxfordshire, has produced 16 MW of fusion power. Now we need to demonstrate energy production above breakeven and design a commercially-viable power station. Magnetic fields are crucial in a tokamak because they trap the hot, fusing plasma When magnetic field is limited the other way to get fusion power gain is by increasing size, as the current world programme has done with ITER – a gargantuan task. We will show how the combination of an efficient Spherical Tokamak design with High Temperature Superconductors could lead to smaller, cheaper fusion machines and correspondingly faster development. This is an exciting prospect that resonates with the public, who are always asking, "when?"

The research is cutting edge and well supported. Science Magazine, July 2014, mentions several private sector initiatives in the world fusion scene and, within this group, Tokamak Energy is the leading European contender. They believe that by thinking differently and exploiting more modern technologies there is a smaller, faster way to fusion. Tokamak Energy has assembled a strong team, including senior members of the fusion community, with close collaborative partnerships with leading UK and US universities (Imperial College, York, MIT, Princeton) and with Oxford Instruments for magnet development. Significant private finance has been obtained for the venture. Their successful development of a high-temperature superconducting toroidal magnet is a major breakthrough and their fully-HTS tokamak a world first.

How would you bring your research 'to life' – what aspects could be explored in a 'hands-on' way by visitors and how will you enable this?

The centrepiece would be the world's first high temperature superconductor tokamak (~1.2m across and 1.5m high) - an impressive piece to examine up close. Additionally, we would have a control desk with remote link-up to a similar tokamak at our laboratory that visitors could run themselves, setting pulse length and plasma heating (within safe limits determined by the control system) so they see what is necessary to make a tokamak plasma. They will see the capacitor banks charge up, press the "fire" button to release the stored energy and watch the plasma formation and evolution on a display. This could even form part of a competition over the week to produce the "best" plasma. We are also designing an app.

We would also have smaller – including busking-style – demos related to fusion, superconductivity and magnetism, e.g. superconductors showing zero resistance when cooled, magnetic levitation, and the magnet-slowing-in-a-copper-tube demonstration of electromagnetic induction.

If selected, what aspects of your exhibit could be adapted in order for your exhibit to have an interactive presence on our website?

A website would be set up to show a live on-line display of the copper coil ST25 tokamak at the laboratory at Milton Park in Oxfordshire – sometimes being operated by the students – and its current status. One video stream would show the experimental area containing the tokamak and others would show the tokamak control and computer displays. Out of hours, archive could be used, and visitors could try the run-your-fusion-reactor app. Links to the Tokamak Energy website show information and videos about the science and our plans for bigger tokamaks leading towards fusion power.

Description of scientific content and background.

The tokamak is one of the foremost devices in fusion research. In the fusion reaction, deuterium and tritium nuclei collide to produce a helium nucleus and a neutron, which in a power station will be used to breed fuel and generate heat for electricity. The hot plasma fuel is trapped by magnetic fields in a torus. We will explain how this works and how Spherical Tokamaks and High Temperature Superconductors can improve things. Tokamak Energy achieved a world first with the operation of their HTS tokamak in August 2014 and in February 2015 will be declaring their plans for HTS fusion devices.

Scientific content will include:

- Superconductivity – conventional vs. high-temperature
- Tokamaks and tokamak operation
    - Electricity and magnetism
    - States of matter
    - Nuclear fusion
- Engineering and material science

The tokamaks for the exhibit have 25cm major radius and 25cm diameter cross-section vacuum-vessels for the plasma. Future power plants will be larger due to radiation shielding and materials considerations. These issues are at the centre of our current research seeking innovative new solutions. Current designs suggest a major radius of at least 1.3m for a power-plant. However, this is still relatively small – not aircraft-hangar-sized!

To assist the Committee members in the assessment process, please list 2 or 3 publications relevant to this research that have been authored or co-authored by the research group.

- A Sykes, M P Gryaznevich, D Kingham, A E Costley, J Hugill, G Smith, P Buxton, S Ball, S Chappell and A Melhem, "Recent Advances on the Spherical Tokamak Route to Fusion Power" IEEE Transactions on Plasma Science, 42, 482-488, 2014
- A E Costley, J Hugill and P Buxton "On the Power and Size of Tokamak Fusion Pilot Plants and Reactors" (submitted to Nuclear Fusion, July 2014)
- D KINGHAM, A SYKES, M GRYAZNEVICH, International Patent (WO2013030554) EFFICIENT COMPACT FUSION REACTOR , 24/8/2012

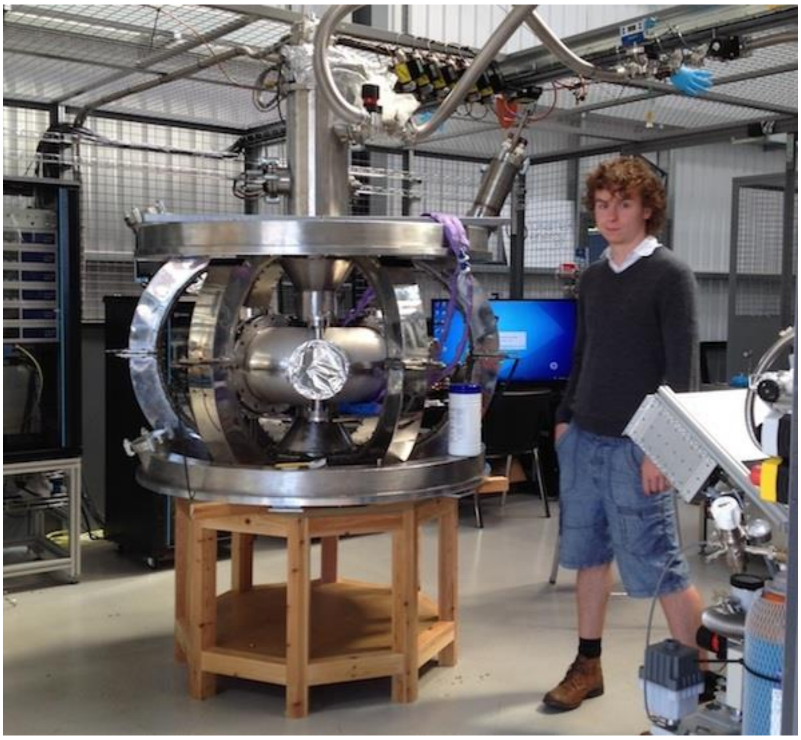
Has your research been publicised already, or will it have been by the time of the Exhibition? Have you had any press coverage of your work?

Past press coverage includes the Financial Times (February 2011), The Engineer (April 2011), The Express (May 2011) and Science Magazine (July 2014) . See www.tokamakenergy.co.uk/press. An event at the Royal Society in February will announce Tokamak Energy's scientific results and future plans, which we expect will draw attention.

Any other comments?

We have an exhibition team with broad skills and experiences working across several of the universities with which Tokamak Energy collaborates. Fellows of the Royal Society Colin Windsor and George Smith have had illustrious careers in neutron scattering and engineering materials, and are both passionate about communicating the excitement of this research to the public. Indeed Colin Windsor has previously been involved in several Summer Science Exhibitions and his experiences will be immensely valuable. Dr Melanie Windridge is an experienced science communicator who has worked with schools for many years. She is also an Educational Consultant with the Ogden Trust, a previous IOP Schools Lecturer (2010) and she has published a general, introductory book on fusion energy. We will work as a team to make the exhibit as engaging and relevant as possible for students while still being attractive and informative for more mature members of the public.

Picture: World's first High Temperature Superconducting tokamak (and summer student)



Weapons of Microscopic Destruction – How your immune system keeps you safe from attack

Summarise your research simply in one sentence/ one brief paragraph. (This should be written for **non-scientists** and will be used as a summary for the committee).

Your immune system is an army of cells protecting you from diseases. It changes throughout life, getting stronger from birth to becoming an adult. But, as we go beyond middle age it begins to weaken. Our research addresses why this happens and what we can do to prevent it.

Summarise why you think this topic will make a good and interesting exhibit for the public and secondary school students.

Exposure to the field of 'immunology' is not common until secondary school, where basic ideas are introduced. However, the public, potentially unknowingly, are aware of the immune system as they are exposed to it through illness, having their children immunised against once prevalent diseases or caring for an older relative struggling to fight off an infection. Recently, there has been much media attention surrounding vaccinations and herd immunity, outbreaks of Flu and Ebola and an increased interest in the challenges society faces due to our ageing population. With inherited immune deficiencies and autoimmune diseases (including multiple sclerosis, rheumatoid arthritis and type 1 diabetes), and reduced immune function due to ageing, a greater understanding of immunity is central to promoting a healthier life.

Our exhibit will explain, using examples from our most recent research; why we have an immune system; how it is developed and regulated; how it identifies friend or foe; how it changes as we age and what affects we can have on it. Our exhibit will also look at how Babraham Institute research, technological advances and understanding of this has an impact on health and disease. Our first example will focus on our recent research into the regulation of our immune system functioning during growth and in response to stress. Our lay friendly graphics alongside images from the laboratory will allow us to explain the roles of each of the cells within the immune system and how regulatory processes affect them. Secondly, we will explore the immune systems' ability to produce billions of different antibodies, their response to potential threats and when it goes wrong (autoimmunity and allergy). In doing this we will highlight our recent advances in methodologies which allow us to study the production of antibodies.

How would you bring your research 'to life' – what aspects could be explored in a 'hands-on' way by visitors and how will you enable this?

Our eye-catching exhibit visualises the immune system in the body and our passionate researchers will explain how their current research relates to the display. To relate the topic to everyday life we will highlight invaders that that are found in food and on our bodies. We'll demonstrate how the immune system recognises friend from foe, by using our life-size magnetic people. These will be the centre of our exhibit and will also demonstrate how our immune system alters as we age.

The production of antibodies and how this changes over time is visualised with a jigsaw game competition, where visitors can compete to build the highest number of antibodies. This game is also available to play on tablets and as a take-home resource. Our online resources will also include video clips, quizzes and images of the immune system cells and our research in action.

If selected, what aspects of your exhibit could be adapted in order for your exhibit to have an interactive presence on our website?

Our antibody building game was developed to run on tablets, but will be adapted to run online via the RS website and our public microsite. Immune Army - here we will upload video clips of our researchers in action and discuss current research, additionally time-lapse, narrated videos of immune system cells and the growth of bacteria from our skin will allow users to relate the immune system function to everyday life. Finally, our take-home resources will be available to download online, in addition to workshop presentations for schools and the opportunity to members of the public to 'ask a scientist'.

Description of scientific content and background.

The exhibit theme – immunology and ageing, relates to everyday life encounters and experiences. The exhibit will explore current research across the institute – the study of how our biology is influenced by varying environmental factors. In particular, we highlight research focussed on the expression of genes responsible for producing billions of different antibodies. Assembling several genes in the genome to build an antibody is the first intriguing step in generating this huge collection. We have developed new methodologies allowing us to study this in depth, if too few antibodies are made it can result in an impaired response to infection or vaccination in the elderly.

Additionally, we study the roles that immune cells play throughout the immune response and characterise pathways of communication and function. These pathways are important pharmaceutical targets to either boost or curtail the immune response. Our studies have provided insights into the molecular mechanisms by which a healthy lifestyle can prevent undesirable immune responses that may result in chronic infections, allergies, autoimmunity and increased risk of cancer. Decoding mechanisms regulating immune cell maturation and function is of interest to those wishing to improve vaccines, combat autoimmune disease, develop tumour immunotherapy or improve the efficiency of organ transplantation.

To assist the Committee members in the assessment process, please list 2 or 3 publications relevant to this research that have been authored or co-authored by the research group.

- Noncoding RNA and its associated proteins as regulatory elements of the immune system. M Turner, A Galloway, E Vigorito *Nature immunology* **15**(6) : 484-91 (2014). DOI: 10.1038/ni.2887
- Inactivation of PI(3)K p110δ breaks regulatory T-cell-mediated immune tolerance to cancer. K Ali, DR Soond, R Piñeiro, T Hagemann, W Pearce, EL Lim, H Bouabe, CL Scudamore, T Hancox, H Maecker, L Friedman, M Turner, K Okkenhaug, B Vanhaesebroeck. *Nature* **510** : 407-411 (2014). DOI: 10.1038/nature13444
- Non-coding transcription and large-scale nuclear organisation of immunoglobulin recombination. MJ Stubbington, AE Corcoran. *Current opinion in genetics & development* **23**(2) : 81-8 (2013). DOI: 10.1016/j.gde.2013.01.001

Has your research been publicised already, or will it have been by the time of the Exhibition? Have you had any press coverage of your work?

- Press release (June 2014) of the discovery of stimulation of immune system against cancer was widely reported e.g. Telegraph
- Participation in Cheltenham Science Festival event 'Are We Too Clean?' resulted in multiple press coverage (2014)
- Exhibit piloted at Cambridge Science Festival Biology Zone (2014)

Any other comments?

Researchers across the Babraham Institute have considerable experience in public engagement activities, with the support of our excellent public engagement team we have participated in numerous scientific festivals and events including, Cambridge Science Festival, Cheltenham Science Festival and the Royal Society Summer Exhibition itself in 2010 and 2012 ('Calcium Signalling – Getting to the heart of the matter' and 'Epigenetics - DNA is not your only destiny').

Additionally, we have fantastic experience of engaging not only schools audiences, but also adult audiences, with events ranging from 'Schools' Day' an in-house event allowing students access into laboratories to carry out research projects and techniques, to our evening panel events which open conversations between our researchers, industrial scientists, clinicians and the general public.

Our ambition is to maximise the impact of our research and to gain feedback from it through interaction and demonstration at the RS Summer Exhibition. By inviting interaction before and after the Exhibition via online engagement through our microsite videos, games and resources we anticipate reaching new audiences. Experience has taught us that interaction with the users of the resources being developed at a very early stage ensures successful engagement. Feedback from teachers, students and members of the public in addition to academic and industrial scientist from across the Babraham Research Campus, has shown us that this exhibit is scientifically relevant. We have also been told that this exhibit is interactive, relatable to everyday life and most importantly – fun!

Quantum light on a chip

Summarise your research simply in one sentence/ one brief paragraph.

Photons are likely to substitute electrons in next generation computers, providing the capability to solve problems beyond the reach of present-day computers using the laws of quantum mechanics. Our research aims at integrating sources, logic gates and detectors of photons on a miniature semiconductor chip as a scalable approach to realise quantum computers.

Summarise why you think this topic will make a good and interesting exhibit for the public and secondary school students.

The ability to harness fundamental quantum mechanical properties to deliver the next step change in technology is hugely exciting and we believe will greatly appeal to the target audience. Quantum mechanics fascinates people with unexpected predictions that often go against everyday intuition. The quantum nature of light, in particular, continues to challenge even the deepest thinkers. However, the interest and appeal of this topic go deeper than just quantum mechanics. Learning how we can use state-of-the-art photonic circuits on a chip to control the quantum nature of light and perform quantum logic operations will also fascinate. Interest will be raised further by appreciating the potential to revolutionize computing by exponentially increasing speed, computing power and security. Scientific research in this area is now moving beyond the realms of lab-based experimentation to real-world exploitation, with major investment coming from governments and companies as the challenge is on to produce the first optical quantum computer.

Our exhibit is further designed to tap into public awareness of light and optics, which will be raised during 2015 (the International Year of Light), providing a unique perspective on the quantum properties and applications by means of demonstrations, both hands-on and computer generated. Visitors will operate models explaining how single 'particles' of light (photons) are generated, showing classical and quantum interference between photons, and quantum logic gates (an already produced and widely viewed animation will support this exhibit). Moreover our hands-on demonstrations will not only exemplify our research but will also increase awareness of the challenges faced in state-of-the-art semiconductor chip fabrication. This has relevance beyond our own circuits (the new Intel 14nm scale process for example) and will be of further immediate interest to the general public.

How would you bring your research 'to life' – what aspects could be explored in a 'hands-on' way by visitors and how will you enable this?

We have already produced an animation of single photon interference on a chip (http://ldsd.group.shef.ac.uk/hong-ou-mandel-effect/), >7000 hits on YouTube). This is being extended to a user-controlled form as part of our exhibit, based on plexi-glass waveguides and light emitting diodes, which are programmed to behave as user-selected classical or quantum sources of light. We will build a large-scale pneumatic system where foam darts (photons) are guided round transparent tubing (photonic circuit) to demonstrate single photon on-chip routing and two-photon interference. The high-tech nanolithography used to create our circuits will be demonstrated through a scaled-up computer-controlled scanning laser system where users can design and 'write' simple circuits on light-sensitive paper to take home. Two user-operated computer simulations will back up these physical demonstrations. The first explains a fundamental property of a single photon: namely if it goes to one detector it cannot at the same time be incident on another detector. The second explains the avalanche multiplication process for detection of single photons.

If selected, what aspects of your exhibit could be adapted in order for your exhibit to have an interactive presence on our website?

We are planning to develop a computer game/app where players guide single photons around a photonic circuit. They would have to negotiate waveguide bends, beamsplitters and interferometers to arrive at checkpoints before photon decoherence sets in. Photon coherence can be boosted at re-phasing stations, and photons may be set to have identical or different colours to exhibit quantum interference or not. This computer game/app will lend itself very well to an interactive form on the RS website. Moreover, an interactive animation on avalanche multiplication may also be envisaged, with user controlled voltage determining the number of electrons produced.

Description of scientific content and background.

Quantum computers will be able to accomplish tasks beyond the capability of classical machines for example in the factoring of large numbers, code breaking and many body simulations to name a few. There are several competing approaches towards this goal. One key requirement is that the technology must be scalable. The approach we pursue based on III-V semiconductors meets this requirement extremely well. It encompasses controllable, deterministic single photon sources (quantum dots), with the quantum dots which form the qubits interacting strongly with light, thus enabling scalable quantum networks to be built up. Quantum optical circuits are thus realised and integrated together on a semiconductor chip, with component sizes ranging from 20nm to ~30μm, capitalising on a highly advanced fabrication technology developed for the micro-electronics industry. The physics involved includes understanding of the factors determining coherence of quantum dot states, tuning of the wavelength of single photons, quantum interference on chip, a network of phase locked quantum emitters, incorporation of on-chip detectors, all accompanied by the technological challenges of integrating the components together in a scalable architecture. The project includes study of new quantum optics and condensed matter physics, combined together with the engineering of large scale integrated circuits.

To assist the Committee members in the assessment process, please list 2 or 3 publications relevant to this research that have been authored or co-authored by the research group.

- Interfacing Spins in an InGaAs Quantum Dot to a Semiconductor Waveguide Circuit Using Emitted Photons, Phys Rev Lett 110, 037402 (2013)
- Monolithic integration of a quantum emitter with a compact on-chip beam-splitter, Appl Phys Lett 104, 231107 (2014)
- Waveguide-coupled photonic crystal cavity for quantum dot spin readout, Optics Express 22, 2376 (2014)
- Observation of bright polariton solitons in a semiconductor microcavity, Nature Photonics 6, 50 (2012)

Has your research been publicised already, or will it have been by the time of the Exhibition? Have you had any press coverage of your work?

We have publicised our work through YouTube video animations, with one available already and another two commissioned and ready by the time of the exhibition. Our research has featured in the blog of the Nature Photonics Editor and also in the News and Views section of Nature Photonics. The University of Sheffield Press Office has also produced several press releases for public consumption.

Any other comments?

We have considerable experience of presentations to the general public including "How to Build a Quantum Computer", "Classical and Quantum Imaging", "Physics of Time Travel" YouTube video (5600 hits), i-tunes audio lecture Physics for Inspiration based on Quantum Optics. Our quantum interference YouTube video is also notable (http://ldsd.group.shef.ac.uk/hong-ou-mandel-effect/) (>7000 hits) in terms of the sort of animation we are able to produce. Applicants include those who have extensive experience of outreach to local schools.