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| **Institution:** Durham University | | |
| **Unit of Assessment:** UoA 9: Physics | | |
| **Title of case study:** High Field Metrology for the ITER Superconducting Magnets. | | |
| **Period when the underpinning research was undertaken:** Between January 2000 and December 2020 | | |
| **Details of staff conducting the underpinning research from the submitting unit:** | | |
| **Name(s):** | **Role(s) (e.g. job title):** | **Period(s) employed by submitting HEI:** |
| Prof. Damian Hampshire<br>Dr. Mark Raine<br>Prof. Ray Sharples | Professor<br>Chief Experimental Officer<br>Professor | October 1990 to present<br>August 2015 to present<br>Jan 1990 to present |
| **Period when the claimed impact occurred:** Between August 2013 and December 2020 | | |
| **Is this case study continued from a case study submitted in 2014?** N | | |

## 1. Summary of the impact

The ITER tokomak is designed to demonstrate the large-scale feasibility of fusion energy generation. It depends critically on superconducting materials to carry the large currents which enable magnetic confinement of the plasma. New metrology techniques developed in Durham are able to characterise the properties of the superconducting strand *under operational conditions,* enabling selection for build of only those which meet the stringent requirements.

ITER maps directly onto the United Kingdom's legal commitment to zero net carbon emissions by 2050. The United States Department of Energy concluded that ITER is the most important large-scale project in the world of the next 20 years.

## 2. Underpinning research

Professor Hampshire and his group have spent the last two decades in Durham researching new instrumentation and measurement protocols to study the current carrying capacity of superconductors. The critical current density, Jc, of a superconductor, is the maximum current density for lossless conduction. This is completely determined by flux pinning at grain boundaries under realistic operating conditions, as this prevents the heating associated with flux motion. In a detailed series of experimental, theoretical, and computational works, Professor Hampshire demonstrated the relationship between Jc and flux flow at grain boundaries in technologically important polycrystalline superconducting materials. Flux pinning becomes much less effective at high magnetic fields and high strains, giving a critical current density which is less than 1% of the theoretical Cooper pair maximum [R1-6].

From 2000, Hampshire and researchers in Durham designed, built and commissioned the first research instruments capable of measuring the critical current as a function of magnetic field, temperature and strain, $Jc(B,T,\varepsilon)$, in long-length superconducting strands. These could perform measurements with nV sensitivity with independent control of all the parameters i.e. high magnetic fields, up to 15T (Durham) and 28T (Grenoble), at cryogenic temperatures from 1.8-14K, and high currents, up to 2KA and under uniaxial strains from -1% to +0.5% [R1]. This research led to the current impact case study because the development of this instrument critically enables the study of Jc under the operational conditions expected for the superconducting materials for use in ITER. The novelty and accuracy of the data, together with the associated understanding of flux pinning and low temperature superconductor behaviour (Ginzburg-Landau theory) led to the development of the '*Durham Scaling Law*', replacing the former standard '*Summers' scaling law'*, previously used by the fusion energy community. This established Durham as a world-leading research centre for novel, accurate measurements of $Jc(B,T,\varepsilon)$ [R2–4] and for developing an understanding of flux pinning in high field superconductors. This was further recognised in 2005 in research building on the *Jc(B,T,ε)* expertise to measure both (isotropic) low temperature superconductors and (anisotropic) high temperature superconductors [R4, R5], funded by a GBP1,600,000 EPSRC grant.

Superconducting magnets manufactured from the isotropic low temperature superconductors $Nb_3Sn$ and NbTi provide the enabling materials technology for the current generation of magnetically confined fusion energy tokamaks. The Hampshire Group has been closely associated with European fusion energy projects and most recently the international ITER project at the CEA Cadarache Centre in Provence. In 2011, Raine and Hampshire set up and managed the European Reference Laboratory (ERL) funded by ITER for approximately EUR2,000,000. This has completed several thousand *Jc(B,T,ε)* measurements and other cryogenic and physical property measurements of the European superconducting strands needed for the ITER magnets using the facilities and research expertise in the Group. This expertise was further recognised between 2012 and 2018 as the group was part of the original GBP2,400,000 EPSRC Fusion Doctoral Training Network (EP/K504178/1) and in 2020, its renewal. Prof. Hampshire also has expertise in magnet design and has recently been granted two patents (GB2562385, GB2558685) concerning a novel design for a superconducting magnet for producing part of the toroidal field (TF) which forms the basis of new designs of magnets that consider the topology of superconducting magnets in fusion tokamaks [e.g. R6].

## 3. References to the research

[R1] N. Cheggour & D. P. Hampshire A probe for investigating the effects of temperature, strain, and magnetic field on transport critical currents in superconducting wires and tapes. *Rev. Sci. Instr.,* 71 4521 (2000) (Cites 66) DOI: 10.1063/1.1324734
[R2] S. A. Keys, N. Koizumi & D. P. Hampshire The strain and temperature scaling law for the critical current density of a jelly-roll $Nb_3Al$ in high magnetic fields. *Supercond. Sci. and Technol.*, 15 991 (2002) (Cites 45). DOI:10.1088/0953-2048/15/7/301
[R3] D. M. J. Taylor & D. P. Hampshire The scaling law for the strain-dependence of the critical current density in $Nb_3Sn$ superconducting wires. *Supercond. Sci. and Technol,* 18 (2005) S241-S252 (Cites 126) DOI:10.1088/0953-2048/18/12/005
[R4] X. F. Lu, D. M. J. Taylor & D. P. Hampshire Critical current scaling laws for advanced $Nb_3Sn$ superconducting strands for fusion applications with six free parameters. *Supercond. Sci. and Technol,* 21 105016 (2008) (Cites 42) DOI:10.1088/0953-2048/21/10/105016
[R5] P.O. Branch, Y. Tsui, K. Osamura & D. P. Hampshire. Weakly-Emergent Strain-Dependent Properties of High Field Superconductors. *Nature Scientific Reports* 9:13998 (2019). (Cites 2) DOI: https://doi.org/10.1038/s41598-019-50266-1
[R6] Hampshire, Damian P., Lee T. S. and Surrey, E. (2018) (i) 'Superconducting magnet for producing part of a substantially toroidal field.' (November 2018) London. Patent number GB2562385. Published November 2018. Granted 12th March 2019.
https://worldwide.espacenet.com/publicationDetails/biblio?DB=worldwide.espacenet.com&II=0&ND=3&adjacent=true&locale=en_EP&FT=D&date=20181114&CC=GB&NR=2562385A&KC=A.

Professor Hampshire has been awarded 15 grants [E7] from the UK, US and EU for research in this field with a total value in excess of GBP4,000,000 highlighting the quality of his research. The underpinning research is all published in the most relevant international peer reviewed journals with over 250 citations to date. Furthermore, [R4] was a research output for Physics at Durham in REF2014, in which only 1 of 300 papers was graded below 2*.

## 4. Details of the impact

Superconducting magnets are an essential enabling technology for magnetically confined fusion energy tokamaks. Conventional electromagnets made of copper or aluminium would either melt or be prohibitively expensive to run, both in terms of cost and energy. Such economic realities also underpin the use of superconducting strands (or wires/cables) for high-field magnets used in

Nuclear Magnetic Resonance techniques (the basis for Magnetic Resonance Imagers in the health sector), and in high-energy particle accelerators, such as at CERN.

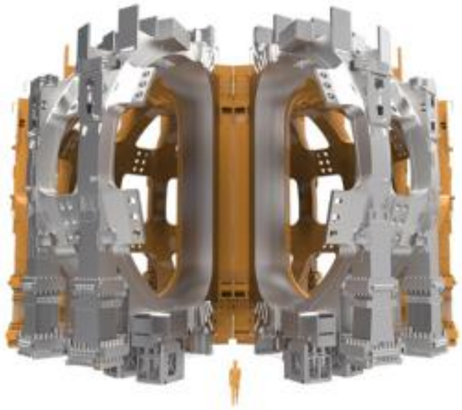

Fig. 1: Toroidal field magnets, with person to scale

Nuclear fusion potentially provides a clean, zero carbon and effectively limitless route to the solution of the world’s energy needs. However, the technical challenges to control a plasma of sufficiently high energy to sustain a net energy output are immense. The main focus for the worldwide effort in nuclear fusion is currently on magnetic confinement and in particular on the ITER tokamak being built in Southern France. The ITER project is a collaboration between 35 nations (including China, the European Union, India, Japan, Korea, Russia and the United States). It will be the world's largest toroidal magnetic fusion device and aims to demonstrate the feasibility of commercial fusion energy.

Fig. 2: Structure of the superconducting strands.

The scale of ITER is immense. 10,000 tonnes of superconducting magnets, the largest and most integrated superconducting system ever built, with a combined stored magnetic energy of 51 Gigajoules, will produce the magnetic fields that will initiate, confine, shape and control the $10^8$K ITER plasma. There are 18 D-shaped coils of $Nb_3Sn$ producing a toroidal field **[E1]** (Fig 1)**,** 10 of which are to be built in Europe, with the other 8 (+1 spare) manufactured in Japan. These, together with the poloidal field (PF) coils of NbTi, amount to one third of the estimated USD22billion cost of the tokamak.

The magnet technology is based on internally cooled “*cable-in-conduit conductors*”, in which bundled superconducting strands, mixed with copper, are cabled together and contained in a structural steel jacket (see Fig 2). These coils will be highly stressed and the reliability of the more than 100,000km of strands used in these superconducting magnets is critical to the progression of the project and to the overall success of ITER. This in turn requires robust, reliable and detailed quality control testing of these materials under functional conditions. This is the key impact generated from the research outputs of Professor Hampshire’s group, given international reach and significance due to ITER. It built on background work by the Durham group on measurements of the superconducting strands for both European and Japanese coils from 2002 to 2011 **[R2]**. Durham was then asked to make the data publicly available for the entire fusion community for use in magnet design and modelling. Dr. Mitchell (Head of ITER Magnet group) confirms “*Durham developed accurate techniques to accurately control temperature and strain and for the first time parameterise the full ITER operational space*” **[E6]**. This has impacted on the design, the quality assurance/reliability, and the construction processes for ITER.

These measurements provided the gold standard in the community and have led to similar facilities being developed at the US government standards laboratory, NIST, by staff trained in Durham **[E2]**. *Fusion for Energy* (F4E), the agency responsible for the development of fusion energy in Europe, established the *European Reference Laboratory* (ERL) at Durham University in 2011 as a contribution to the ITER project. The ERL in Durham has subsequently received more than EUR2,000,000 in funding from F4E between 2011 and 2018 to provide thousands of characterisation measurements of the superconducting strands to be used in the 10 (of 18 +1 spare) huge TF magnets/coils and one of the PF coils in the ITER magnet system **[E7]**. These measurements are critical and have ongoing impact at ITER - if one TF coil fails, the topology of the plasma and vacuum jacket within the TF magnets means that inserting a new TF coil would cause a 2-year delay for repairs/replacement. By January 2020, the measurements for F4E were completed.

This work in Durham included a formal quality assurance process for F4E. This comprises an independent verification of the strand supplier performance tests and is critical to acceptance of the superconducting strands prior to incorporation into the ITER magnet cables by the cable manufacturers. The experience in 2008 at the Large Hadron Collider at CERN **[E3]** shows that it takes only one magnet component failure to bring a machine of this complexity to a halt. Strands that do not pass the Durham tests are not used in the ITER tokamak.

Durham University's research and collaboration with F4E secured reliable operation of the TF and PF coils, and informed decisions leading to improvements in productivity and resource-use efficiency:

1. The quality of the superconducting composite strands is exceptionally reliant on the quality of the heat treatments used to diffuse the Sn in the Nb wire to produce the superconducting $Nb_3Sn$. However, this can also lead to unwanted diffusion into the high purity copper within the strands. Key verification tests undertaken by the Durham ERL between March 2013 and June 2014 identified several strands where the copper impurity level violated specification, contrary to supplier's data. This resulted in a review and round-robin tests were initiated by F4E and conducted by Durham, Twente, CERN, and the ITER Organization, which confirmed the Durham results. From 2014 onwards this has resulted in F4E avoiding strands which would have compromised the reliable operation of the European TF coils in the ITER tokamak. Durham's analysis allowed F4E to ensure the stability of the European TF coils resulting in what Thierry Boutboul, Senior Technical Officer, described as a '*technical positive impact*' **[E4]**.


Fig. 3: Heat treatment oven for the TF D-shaped magnets in Fig. 1

2. The brittle nature of the $Nb_3Sn$ polycrystalline compound means that the wires have to be baked in ovens the same size of the resulting coils (see Fig 1 and 3), on size scales which make it very difficult to ensure temperature homogeneity. The magnet coils themselves cannot be tested before assembly into ITER, so instead test samples are placed all around the coil in the oven. Durham produced, supplied and measured the critical current in hundreds of these test samples between October 2012 and May 2018. F4E said: '*Thanks to Durham work and its very collaborative attitude the homogeneity of both … ovens has been confirmed, which is a technical positive impact*' **[E4]**.

3. In 2015, operational technical difficulties led to discrepancies in some of heat treatments, and it was not clear whether these coils would meet specifications. The Durham group simulated these and demonstrated that there was no impact on the Jc properties of the coil, which led F4E to comment that '*I would like to stress the reactivity and the collaboration spirit of Durham staff which enabled F4E and ITER IO to get this confirmation and not to waste time … but to continue with the fabrication of the coil. This had a clear schedule positive impact on the project.*' **[E4]**.

Durham's research activities in functional metrology of superconductors continues to have a major impact on the ITER construction programme. The immediate impact is technical, but has significant political consequences. ITER commissioning has spiralled away from its initial 2016 schedule, with first plasma now expected in December 2025 and the budget is quadruple its original size **[E5]**, compounding political sensitivities. Thus, maintaining the speed of construction, while ensuring the reliability and stability of the magnets, so that at switch-on plasma containment is achieved is crucial to the future political will and decision making of the collaborating countries in the decision to build fusion-based electricity power stations.

**5. Sources to corroborate the impact**

[E1] ITER webpage on magnets (https://www.iter.org/mach/magnets).
[E2] Journal paper published by NIST staff: Unified scaling law for flux pinning in practical superconductors: III. Minimum datasets, core parameters, and applications of the extrapolative scaling expression, Ekin et al., 2017, Superconductor Science and Technolology 30:033005; DOI: 10.1088/1361-6668/30/3/033005; available through the NIST website: https://www.nist.gov/publications/unified-scaling-law-flux-pinning-practical-superconductors-part-3-extrapolations
[E3] The damage that derailed the Large Hadron Collider, New Scientist article, 11 December 2008 (https://www.newscientist.com/gallery/dn16254-damage-that-derailed-higgs-hunt/).
[E4]. Testimonial from Senior Technical Officer**,** Magnets Team/ITER Delivery Department. Fusion for Energy. June 2019.
[E5] Fusion energy pushed back beyond 2050, BBC News article, 11 July 2017 (https://www.bbc.co.uk/news/science-environment-40558758).
[E6] Testimonial from ITER Magnet Division Head, 11 January 2020.
[E7] List of grants awarded to Durham University