Institution: University of York

Unit of Assessment: 9, Physics

Title of case study: The impact of York's plasma science on the design and construction of ITER

1. Summary of the impact (indicative maximum 100 words)

Although the world will have some time to wait until the full impact of fusion energy is realised, there is substantial non-academic impact from plasma science on the design of ITER. This €13Bn+ international facility, under construction in France, is designed to demonstrate the technical feasibility of fusion energy. Our research on plasma eruptions (like mini solar flares), identified the need to protect ITER plasma facing components from large, localised thermal loads. In addition, the antennas for radio-frequency heating of ITER plasmas needed to be designed to take account of the filamentary density structures that we predicted to be associated with these eruptions.

2. Underpinning research (indicative maximum 500 words)

The most advanced fusion energy device, called a tokamak, confines plasma using magnetic fields. Tokamak plasmas are vulnerable to a sequence of repetitive plasma eruptions called Edge Localised Modes (ELMs - like mini "solar flares"). Professor Howard Wilson developed the fundamental theory for these eruptions that predicted: (i) ELMs occur when the edge plasma pressure gradient exceeds a critical value [1-3] and (ii) the eruptions violently eject filaments of hot plasma that could strike (and damage) the components of the fusion reactor (2004-present) [4]. The latter prediction was important as prior to this theory it was thought that ELMs blew off a uniform shell of plasma into the tokamak exhaust region with little impact on other components. The theory and its consequences were not universally accepted, so following his move to York in 2005, Professor Wilson worked with experimentalists on the MAST tokamak at Culham Centre for Fusion Energy to confirm the prediction of the existence of filaments using high speed camera images of the plasma [5,6]; erupting filaments during ELMs have since been seen on all the world's leading tokamaks, transforming our picture of what an ELM is. Specifically, the theory predicts, and experiment observes, that hot plasma filaments from ELMs can strike tokamak components, producing localised high thermal loads. While these thermal loads are tolerable on today's tokamaks, on ITER where the thermal energy will be much greater, they are likely to cause excessive damage. Without Wilson's theory to guide experiments to search for filamentary structures, it is unlikely they would have been detected in today's tokamak experiments (they exist for just 50 microseconds, and travel at 10's km/s). Consequently, the threat they pose to ITER components may not have been appreciated, and the necessary additional protection not built into the design of components.

The initial theory for the nonlinear evolution of ELMs, including the prediction of erupting hot plasma filaments, was developed by Professor Wilson in 2004, just before he moved to York in 2005. However, it was not universally accepted at that time, so he continued to work in this area, quantifying the theory's predictions [4] and working with experimental colleagues to test it against experiments on MAST [5, 6]. The theory guided new high performance computer simulations of ELMs by the York group and others [7]. These experiments and simulations confirmed the theory and firmly established filamentary eruptions during ELMs as a key issue for future tokamaks. In 2006, Professor Wilson was awarded a £658k EPSRC grant to simulate plasma eruptions on high performance computers [11]. This funded the development at York of a new ELM simulation code in 2009, called BOUT++ [8], led by Dr Ben Dudson initially as a post-doc at York and then as a Lecturer there since 2009. BOUT++ is an on-going project working towards a quantitative predictive capability for ELM filaments on ITER [8-10]. Prof Wilson was awarded the 2013 American Physical Society "John Dawson Award for Excellence in Plasma Physics Research" with three US collaborators, for work that includes this research.

3. References to the research (indicative maximum of six references)

Journals listed in the references below are all peer reviewed; citation count from Web of Science

Key references for York staff on plasma eruptions

[1] H R Wilson, et al *Magneto-hydrodynamic stability of the H-mode transport barrier as a model for edge-localised modes: an overview* Plas Phys Contr Fusion **48** A71 (2006) (51 citations)

[2] P B Snyder, K H Burrell, H R Wilson, et al *Stability and dynamics of the edge pedestal in the low collisionality regime: physics mechanisms for steady state ELM-free operation* Nucl Fusion **47** 961 (2007) (64 citations)

[3] H R Wilson, Invited talk at IAEA Technical meeting on H-mode physics and transport barriers *Magneto-hydrodynamic stability of the H-mode transport barrier as a model for edge-localised modes: an overview* (2005)

[4] H.R. WILSON, et al *Proceedings of the 21st IAEA Fusion Energy Conference, Chengdu, on CD-ROM: IAEA-CN-149,* paperTH/4-1Rb (2006)

[5] A Kirk, H R Wilson, et al *Structure of ELMs in MAST and the implications for energy deposition* Plas Phys Contr Fusion **47** 315 (2005) (48 citations)

[6] A. Kirk, B. Koch, R. Scannell, H.R. Wilson, et al *Evolution of filaments during Edge Localized Modes in the MAST tokamak*, Phys Rev Lett **96** 185001 (2006) (64 citations)

[7] P B Snyder, H R Wilson and X Q Xu *Progress in the peeling-ballooning model of edge-localised modes: numerical studies of nonlinear dynamics* Phys Plasmas **12** 056115 (2005) (79 citations)

[8] B D Dudson, et al; *BOUT++: A framework for parallel plasma fluid simulations* Computer Physics Communications **180** 1467 (2009) (22 citations)

[9] X Q Xu, B Dudson, P B Snyder, M V Umansky and H R Wilson "*Nonlinear simulations of peeling-ballooning modes with anomalous electron viscosity and their role in edge localized mode crashes*" Phys Rev Lett **105** 175005 (2010) (14 citations)

[10] B D Dudson, X Q Xu, M V Umansky, H R Wilson and P B Snyder "Simulation of edge localized modes using BOUT++" Plas. Physics Control. Fusion **53** 054005 (2011) (7 citations)

[11] EPSRC grant EP/D065399/1; PI H R Wilson (University of York); "Theory of Explosive Plasma Instabilities" (2006-2010) £658k

4. Details of the impact (indicative maximum 750 words)

A key step to fusion energy is the construction of the €13Bn+ ITER tokamak, scheduled for completion towards the end of the decade. ITER is not an academic research facility: its goal is to integrate plasma science, technologies and materials science to provide the first demonstration of the technical feasibility of fusion energy. Furthermore, the construction of ITER involves industrial partners across the world, including the UK, who benefit from the contracts it provides and the technical skills it develops. Research that has an impact on the technical feasibility of constructing ITER is therefore a non-academic impact, immediately benefitting all the international partners involved in the project.

Research performed at York on ELMs has had an impact on the ITER design in three areas: (1) design of components close to the plasma surface; (2) radio-frequency plasma heating systems, and (3) developing ELM control techniques. Before our prediction that ELMs eject hot filaments of plasma, it was thought that most of the heat lost in these events would be transferred smoothly over the exhaust region at the bottom of the tokamak. To handle the high heat loads expected, this is made from tungsten on ITER. With our new prediction that hot plasma filaments could be ejected far from the core, concern started to grow that they could damage other components close to the plasma if not protected. This became a key issue for ITER.

The plasma physics research for ITER is carried out by the research institutions of the ITER parties (European Union, Russia, United States, Japan, South Korea, China and India), coordinated by seven International Tokamak Physics Activity (ITPA) Groups which operate under the auspices of ITER (http://www.iter.org/org/team/fst/itpa). The Pedestal and Edge Physics ITPA Group is responsible for research into ELMs, ensuring the science of the international research community is fed into the ITER design and that urgent research needs for the construction of ITER are addressed. As a result of his contributions, Prof Wilson was appointed chair of this group of the world's top experts in this field (about 35) during 2007-2011 (he remains a formally appointed EU member). This position provides a strong pathway to impact on ITER for Prof Wilson's research on plasma filaments, which has now grown into a major research activity of the group because of its importance for fusion. Specific examples of the impact of York on the ITER design are :

(1) The detail design of ITER's first wall components: these have to withstand the localised time-averaged heat fluxes from the ELMs which are predicted to concentrate on particular areas of the first wall. Predictions of the ELM filament structure have been used to evaluate the most exposed locations to loads from ELMs and the beryllium-clad protection of the ITER first wall has been upgraded to a higher capability (4.7 MWm^{-2} instead of 2 MWm^{-2}) to cope with them. The final design review of ITER vacuum vessel protection took place in April 2013 (http://www.iter.org/newsline/264/1556).

(2) The detailed design of the radio-frequency antennas for plasma heating on ITER: these must be positioned close to the plasma to be effective and therefore need to be protected to avoid damage by the erupting filaments of hot plasma. As well as the risk of damage, the effectiveness of the RF antennas for heating the plasma is influenced by the localised plasma density structures associated with ELMs. For example, the number of straps on ITER's antennas is designed based on the spatial structure of the filaments as predicted by the original "peeling-ballooning" theory for ELMs proposed by Professor Wilson and quantified for ITER through research of the team of scientists of the ITPA group chaired by him. The preliminary design review of the ICRH antenna, costing around €24M, took place in May 2012 (http://www.iter.org/newsline/225/1193) and the final design review will take place in 2015.

3) ELM control schemes in ITER: In addition to large power fluxes on the ITER first wall it is predicted that the large transient ELM heat loads will rapidly erode the tungsten in the exhaust region of ITER, and therefore ELMs will need to be controlled. Our theory, confirmed through experiments coordinated by the ITPA PEP group, predicts that ELMs occur when the pressure gradient at the edge of the plasma exceeds a threshold. This led scientists at General Atomics (US) and CEA (France) to develop a control system using an arrangement of coils around the plasma to degrade the confinement, and relax the pressure gradient to switch off the ELMs. This remains an active area of research around the world, but the technique appears to work and a ~€100M ELM control coil system is now being integrated into the ITER design whose final design review will take place in December 2013. Although we have only played a small role in the design of the control system, it is motivated by our theoretical understanding of the mechanism that drives the plasma eruption.

The research leading to this impact is now international, involving many scientists around the world. It was, however, initiated by our theoretical model for ELMs and the eruption of hot plasma filaments, and fed into the ITER design through the ITPA PEP group chaired by York through Prof Wilson during 2007-2011. Concerning the theoretical development, Professor Wilson led this research since 1998 while he was at Culham Centre for Fusion Energy and then York (since 2005). A new computational code, ELITE, was used to understand the ELM trigger and, although initiated by Professor Wilson, benefitted from a strong collaboration with General Atomics (US); that collaboration continues to this day (the research of the 4-man GA-York team has been recognised by a prestigious 2013 American Physical Society award, see above). The nonlinear theory was initiated just before Professor Wilson's move to York, working in collaboration with Professor Steve Cowley, then of Imperial College. However, at that time there was some doubt about the relevance of the theory. Research continued at York (and also stimulated related research around the world) to further advance the theory and test it against experiments. Research at York includes deriving the direction of the eruptions, and the development of a new nonlinear MHD high performance computer code to simulate ELMs, BOUT++. Led by Dr Dudson at York, the BOUT++ project benefits from close collaboration with Lawrence Livermore National Laboratory (US).

5. Sources to corroborate the impact (indicative maximum of 10 references)

Corroborating letter from Plasma Confinement and Modelling Section Leader, ITER Organisation