Institution: The University of Huddersfield

Unit of Assessment: 9 Physics

Title of case study: Accelerator Applications

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

Our development and demonstration of the world's first ns-FFAG accelerator (EMMA) and our expertise in exploiting and extending the capabilities of GEANT4 simulations have enabled us, in a relatively short time, to demonstrate societally significant applications of advanced particle accelerator technology. This research, which has garnered significant commercial and media attention, has demonstrated the feasibility of compact, reliable and affordable proton machines for cancer therapy [C], radioisotope production [A,B] and muon [F] and neutron [E] production, thereby offering UK industry a technological lead in a potentially enormous international market. Additionally, our research in accelerator driven technologies had played a significant role in establishing the scientific and political case for the construction of the 1.5b€ European Spallation Source in Lund, Sweden, and is influencing developments at Fermilab in the US [E,F].

2. Underpinning research (indicative maximum 500 words)

The underpinning research programmes which have led this impact has three components:

(a) The design and delivery of innovative compact particle accelerators: The £7.5M CONFORM project, funded by the RCUK Basic Technology program from 2007, developed a new, compact and exploitable form of accelerator, the non-scaling fixed-field alternating-gradient (nsFFAG) accelerator [1]. Huddersfield's involvement (from 2008) was initially led by Prof Cywinski, the joint coordinator of the work package investigating applications that this technology could open up in the fields of healthcare, energy production, and materials studies. Prof Edgecock, coordinator of the work package that built EMMA, the world's first nsFFAG machine, and managed its first successful operation in 2011, joined Huddersfield at 0.5FTE in 2010, whilst Prof Barlow, the Principal Investigator of CONFORM project, joined Huddersfield in early 2011.

The nsFFAG brings together the fixed field and high duty cycle of a cyclotron (but not its relativistic limitations) with the strong focussing of a synchrotron, by using magnets whose field varies with position but not with time. This field variation provides the focussing. In a conventional (scaling) FFAG the beam optics does not change during particle acceleration, which enables resonances to be avoided but severely constrains the form of the field. Relaxing this constraint enables simpler magnets and a smaller beam pipe to be deployed. We proposed that the resonances would not destroy the beam as the rapid acceleration meant that they are passed through quickly and this was verified with the first acceleration in EMMA in 2011, and has been confirmed by EMMA's operation since then [1].

Having proven nsFFAG technology we have thus opened the door to development of cheap, simple and compact proton machine(s) providing synchrotron energies at cyclotron currents, with simple magnets and low losses. We are researching potential applications in medical physics for proton and charged ion radiotherapy, for medical isotope production, and for the production of muons and neutrons for boron neutron capture therapy (BNCT), security and condensed matter studies.

(b) The exploitation and development of GEANT4 simulations of particle-beam interactions

Our expertise in GEANT4, a modern and very general simulation code developed for particle physics, has enabled us to explore, evaluate and optimise particle-target interactions and the associated production of pions, muons, neutrons and radioisotopes, whilst also extending the capabilities of GEANT4 to deliver reliable results at significantly lower proton energies (<20MeV). For example, Siemens-funded research has led to models for accelerator-driven low energy proton production of currently exploited and novel radioisotopes for PET and SPECT medical imaging [2] and for optimised low energy neutron production for BNCT. At higher proton energies we have made significant progress in optimising the target material, geometry, and muon production rates for the DAEdALUS project [3], for the ISIS muon facility [4], and for stand-alone MuSR facilties now

being considered for construction by Fermilab and Brookhaven DOE laboratories.

(c) The development of the scientific and political case for the European Spallation Source
The major scientific, political and socioeconomic impetus to build the 1.5b€ ESS was provided by the EU FP7 ESS Preparatory Phase Project (2008 – 2010), which led to the multinational decision to build ESS in Lund in Sweden. Huddersfield was the only UK HEI participating in ESS-PPP and Cywinski played a major role both leading and participating in a number of the ESS-PPP work packages. Prof Seviour worked on RF sources, and was also editor of the ESS Conceptual Design Report Accelerator chapter and lead member of the Cross Functional Working Group on reliability of the whole ESS Facility. Huddersfield's original involvement with neutron instrumentation and general neutronics, has thus evolved to include the design of the target, evaluation of induced radiation in the accelerator, and the accelerator itself.

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

[1] S.Machida, R.Barlow*, R.Edgecock*, C.Johnstone[+] *et al*, (EMMA collaboration, 56 authors) *Acceleration in the linear non-scaling fixed-field alternating-gradient accelerator EMMA*. (2012) Nature Physics, 8, 243-247, DOI:10.1038/nphys2179 #

[2] N.Ratcliffe*, R.Barlow*, A.Bungau*, C.Bungau* and R.Cywinski[*], *GEANT4 Target Simulations for Low Energy Medical Applications*, (2013) Proc. of the 4th International Particle Accelerator Conference. IPAC 2013. JACoW, Shanghai, China, pp. 3717-3719. ISBN 978-3-95450-122-9

[3] A.Bungau*, R.Barlow* *et al* (19 authors) *Proposal for an electron antineutrino disappearance search using high rate ^{8}Li production and decay*, (2012) Physical Review Letters 109 141802 DOI: 10.1103/PhysRevLett.109.141802 #

[4] A.Bungau*, R.Cywinski*, C.Bungau*, *et al* (5 authors) *Simulations of surface muon production in graphite targets* (2013) Physical Review Special Topics – Accelerators and Beams, 16, 014701 DOI: 10.1103/PhysRevSTAB.16.014701 #

[5] S.Peggs, R.Seviour* *et al* (72 authors) *Conceptual Design Report*, (2012) ESS, Lund ISBN 978-91-980173-0-4

papers selected to indicate quality of underpinning research

* denotes Huddersfield author, [+]Visiting Professor at Huddersfield. Non-Huddersfield lead authors are given in refs 1 and 5 for bibliographic completeness.

Grants supporting the research

Barlow (PI), Cywinski, Edgecock *et al,* EPSRC EP/E032869/1 *The Non Scaling Fixed Field Alternating Gradient (NS-FFAG) Accelerator* 1/4/07-31/3/11 £7,472,363

Cywinski *et al,* EU FP7 Project Reference 202247 *The European Spallation Neutron Source (ESS)* 2008- 2011 Project Cost €6,612,468 Project Funding €4,999,995

Barlow, Cywinski, Direct funding from the ESS (Lund) Project 2013 *Induced Activity in ESS Accelerator Components* Phase 1 1/02-1/08/13 £29,500 Phase 2 1/11/13-1/3/14 £25,000

Edgecock EU FP7 EUCARD 2011 £17,270 EUCARD2 1/05/13-1/05/17 £151,857

Bungau (PI), Edgecock STFC ST/J001821/1 1/04/12 -31/03/16 *Proposal for the Continuation of High Power Target Studies* £203,278

Edgecock STFC ST/J001910/1 1/04/12-31/03/15 *Front End Test Stand* £15,015

Seviour STFC+Siemens CASE ST/I00598X/1 1/10/11-30/09/15 *Neutron Source for Security Applications* £108,940

Cywinski EPSRC+Siemens CASE EP/H50124X/1 1/10/09-30/9/14 *Medical Isotope Production* £96,838

4. Details of the impact (indicative maximum 750 words)
Impact on Industry and Medicine and beyond.

Our research in applied accelerator technologies and particle/target interactions has been widely welcomed by the industrial and medical sectors:

As a consequence of our research programmes and our approach to research, Siemens AG has established a formal collaboration with Huddersfield, and awarded our International Institute for Accelerator Applications (IIAA) the status of Siemens Official Technology Partner. We continue to work with Siemens on the broader applications of low energy proton accelerators through two CASE studentships, through contracted research and through our operation of a £0.5M ion source provided by Siemens to the IIAA on extended loan. While much of the work with and for Siemens is covered by Non-Disclosure Agreements, one example in the public domain is our work on alleviating the global ^{99m}Tc drought by exploring the feasibility of low energy proton accelerator production of this and alternative radioisotopes. We have demonstrated the potential of local hospital based radioisotope production, and of the deployment of much shorter lived isotopes for PET and SPECT, and even for cancer therapy, thereby presenting new industrial routes to the reliable production and deployment of medical radioisotopes. Siemens acknowledge that the IIAA "…*is providing an invaluable and recognisable service, informing and influencing our own internal Research and Development programmes.*" [A].

Additionally the US company Particle Accelerator Corporation has collaborated in novel ns-FFAG design. As a consequence PAC "…*has now established a UK subsidiary of PAC, ie PAC (UK) to be located at the University of Huddersfield in the 3M Buckley Innovation Centre. Huddersfield's research programmes will undoubtedly impact future designs and development of ns-FFAG technology for the benefit of both industry and society on both sides of the Atlantic…"* noting *"…it is important to continue our collaborative work on next-generation commercial and medical accelerators…*". PAC is currently "…*in the process of licensing our latest innovative technology with Huddersfield to further our close collaboration, specifically targeting the need for new, compact sources of radioisotopes…*" [B].

Our research in low energy proton/target interactions for neutron delivery for Boron Neutron Capture Therapy has been described by University Hospital Birmingham NHS Foundation Trust as being "…*essential in shaping our plans for clinical application of BNCT using the Dynamitron accelerator in Birmingham…*". We are also told "…*our on-going collaboration is critical to our clinical programme...*" [C].

Although the construction of the European Spallation Source (ESS) in Lund, Sweden has not yet started, our impact on industry is well underway. As part of the Framework 7 ESS Preparatory Phase Project (ESS-PPP) Cywinski organised and opened the ESS Industry Day meeting in Copenhagen in February 2010. Over 400 pan-European industrialists and politicians attended to hear about the use of neutrons for materials research, about how ESS will be built and the facility's impact on society, and particularly about what neutrons can do for industrial R&D, and the potential for industrial engagement in the construction of ESS [D].

ESS will be a flagship of European science, comparable in stature to such international facilities as CERN, ESRF and the Institut Laue Langevin. It should be noted that "…*the impact of the University of Huddersfield's research on the ESS project has been significant…*" : the ESS-PPP in which "…*Cywinski played a leading and pivotal role, not only helped to secure the decision to build ESS, but also the decision of where in Europe it should be built…*". Additionally, "…*Seviour has been a key member of the ESS accelerator design team, influencing the final configuration of the ESS driver and being a very capable ambassador for the project…"* [E].

Just as our research has influenced the ESS project, we are now influencing the US DOE's Fermilab future plans for Project X on the other side of the Atlantic. Indeed Fermilab recognises that our "…*research may well have implications for the configuration and scope of such future high power proton accelerators for particle and nuclear physics…*" and that Fermilab has "…*benefited from our collaboration with the University of Huddersfield on the possibility of developing intense muon sources based on high power proton accelerators…*" [F]

Impact in the Media

The national and international press has shown great interest in our accelerator projects. News Focus in Science devoted two pages to EMMA in 2010 whilst the Engineer and Physics World discussed our ns-FFAG research (in April and May 2011). In June 2011 The Mail on Sunday colour supplement featured "*This is Emma. She's going to save the world (and cure cancer)*". The article showed how EMMA has proven the ns-FFAG concept, and is now being used to help design better

accelerators for radiotherapy, future particle colliders, and for highly reliable powerful proton accelerators producing neutrons [G]. Correspondingly reports of EMMA went global, with the accelerator development featuring on Fox News in US, and featured in Horizons Business on BBC World News with viewing figures approaching 100 million. In total there are over 32,800 Google hits referencing EMMA alone.

We have also scripted and produced two broadcast quality and copyright-free videos describing accelerators and their applications [H]. The first is a 25 minute educational animated documentary film about our research carried out as part of the CONFORM project. Presented by Professor Lord Robert Winston, the film raises public awareness of the role of particle accelerators in science, technology and medicine, and the construction of EMMA, at Daresbury Laboratory and covers the history of accelerators, and ns-FFAG technology and its potential applications in proton/hadron cancer therapy. It has been watched approximately 4000 times on youtube alone and over 1000 DVDs have been distributed to schools, the press, politicians and the public across Europe.

In the second Sir Patrick Stewart presents an introduction to the European Spallation Source, explaining that it is a major science facility that will provide the world's most intense beams of neutrons to study materials at the atomic level, probing deeply into materials with unprecedented clarity. Sir Patrick explains how it will be one of the most important research facilities in the world, enabling developments in drug design, magnetic materials for data storage, ceramics for engineering, biocompatible materials, hydrogen fuel and processes for capturing carbon. The video is available on line and has been viewed over 32,000 times, and over 500 DVDs have been distributed to politicians and journalists.

The CONFORM movie was invited to be exhibited at the International Festival of Popular Science and Educational Films “World of Knowledge” in St Petersburg, Russia in October 2011, whilst the ESS movie was one of ten shortlisted for the US National Science Foundation’s International Science and Engineering Visualization Challenge in the same month. The ESS movie was also shown and distributed at the ESS Industry Day meeting in Copenhagen.

The press coverage and the videos have led directly to a remarkable upsurge in public interest in our research, precipitating many requests for public lectures, as described below.

Impact through outreach

Members of the group have a long history of activity in outreach and public engagement with many different audiences and have brought this experience to enhance the wider impact of this research Activities include dozens of invited talks to 6th formers in schools; to adults at ‘Café Sciéntifique’, SciBar, TEDx, and Philosophical Society events, and to industrial networks such as the Nuclear Institute. Cywinski and Barlow are regular speakers, usually to audiences of 50 or more. The growing frequency of invitations from networked organisers of these events is indicative of growing public awareness of and interest in our research.

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

[A] Endorsement from Head of Strategic Development, Siemens plc

[B] Endorsement from Senior Accelerator Scientist at Particle Accelerator Corporation US

[C] Endorsement from Head of Medical Physics, Queen Elizabeth Hospital, Birmingham

[D] http://news.cision.com/european-spallation-source-ab/r/ess-industry-day--more-than-400-industrialists-showed-great-interest-for-a-european-flagship-project,c473448

[E] Endorsement from Special Adviser Science Village Scandinavia and Director-General European Spallation Source (2007-2013)

[F] Endorsement from the Associate Laboratory Director for Accelerators, FermiLab

[G] http://www.dailymail.co.uk/home/moslive/article-2001548/Electron-Model-Many-Applications-Technology-save-world.html#ixzz1gzvPcQ2H- ;News Focus in Science (8 January 2010 Vol. 327 no. 5962 pp. 142-143)

[H] CONFORM video on http://vimeo.com/19788097, ESS video on http://www.youtube.com/watch?v=KG3Upzc3NGY http://www.youtube.com/watch?v=EIBIMGEmR5I, and http://vimeo.com/19475801