Institution:	The University of Oxford
Unit of Assessment:	9 - Physics
Title of case study:	How To Build a Particle Accelerator

1. Summary of the impact

This outreach event presents the principles and applications of particle accelerators. It has resulted in increased interest in and knowledge of particle accelerators by over 7,700 schoolchildren; greater knowledge and ability of schoolteachers to incorporate content, demonstrations and experiments related to accelerator science into their teaching; and wider awareness in the general public of many kinds of particle accelerators and their uses (e.g. in medicine and industry). The beneficiaries extend beyond audiences of shows presented by the University of Oxford through delivery by other institutions in the UK and Germany, and downloads of online material.

2. Underpinning research

A substantial body of work on the design, development and operation of particle accelerators has been carried out in the Department of Physics at Oxford over the last twenty years, and led in 2006 to the establishment of the John Adams Institute for Accelerator Science (JAI). The JAI is co-hosted by the Departments of Physics at Oxford, Royal Holloway University of London and (from April 2012) Imperial College, but research described here was undertaken by Oxford physicists.

Whatever their size, particle accelerators share common requirements for *acceleration*, *control*, *collision* with the intended target and *detection*. Highlights of this research include

- Contributions by Professors Brian Foster, Philip Burrows and current JAI Director Andrei Seryi to the technical design of the International Linear Collider (ILC), a proposed new superconducting accelerator and collider experiment [1]. Foster is Director (Europe) for the Global Design Effort that has coordinated worldwide R&D since 2007. Foster has been a Professor at Oxford since 2003, Burrows since 2006 and Seryi since 2010.
- Development by Burrows of state-of-the-art accelerator control through beam position monitor (BPM) signal processing [2], feedback processors, and amplifier systems, as part of the research and development for the ILC, the Compact Linear Collider and other future collider experiments.
- Development and demonstration by Foster and others of novel 'laser-wire' beam diagnostics for the control of future colliders, using lasers to monitor non-invasively the transverse position of electron beams with μm cross-section [3].
- Professor Ken Peach, PDRA Takeichiro Yokoi and graduate student Suzanne Sheehy were part of the CONFORM collaboration that achieved acceleration in the first operational implementation of an alternative design of compact electron accelerator in 2011, motivated by requirements in medical physics. In parallel, they developed with PDRA Holger Witte a design for a proton and carbon ion accelerator using the same principles and patented the resulting magnet design. Peach was the founding Director (2005-10) of the JAI and retired in 2011; Yokoi (2007-2012), Sheehy (2007-10) and Witte (2007-11) also all worked in the JAI at Oxford.
- Development and demonstration by Dr George Doucas of the use of Smith-Purcell radiation generated by particles passing over a grating to measure longitudinal particle bunch shape [4], which is leading to improved control of accelerators with ultra-short particle bunches. Doucas was a Senior Research Associate (1991-2007) in Oxford until his retirement in 2007.
- Developments led by Dr Riccardo Bartolini through research in non-linear beam dynamics at the Diamond synchrotron light source [5] have improved its performance. This was exemplified by Diamond attaining the world record for vertical beam confinement ('emittance') in storage rings in 2009, representing an unprecedented reduction of beam size and divergence. Bartolini has held a joint appointment as a lecturer at Oxford and Head of the Accelerator Physics Group at Diamond Light Source since 2007.

The applications of particle accelerators not only to particle physics but to other physical sciences, life sciences and medicine, and the characteristics necessary for successful implementation, have guided some of the JAI's research. For example, the constraints of medical applications have guided new accelerator designs; the stability and performance required for practical synchrotron light sources have motivated better monitoring and control [4,5]; and particle detectors first developed for the ILC have been adapted for spatial imaging in mass spectrometry by Dr Andrei Nomerotski (Lecturer in Oxford 2005-12). The awareness of these requirements and the capabilities that accelerators can offer have thus been an integral part of this research.

3. References to the research *(Oxford authors underlined; *denotes 3 most indicative of quality)*

1. *B. Foster, P. Burrows and A. Seryi co-editors with 41 others (2013). The International Linear Collider Technical Design Report: Volume 3: Accelerator (Parts I & II). ILC-REPORT-2013-040. http://www.linearcollider.org/ILC/Publications/Technical-Design-Report
   This design report to the International Committee for Future Accelerators is the culmination of over five years' work as part of the Global Design Effort of the ILC project. It sets out the blueprint for the design of the ILC accelerator. Burrows was the lead editor of sections 3.6 and 4.5 in addition to being an editor of the entire volume.

2. J. Resta-Lopez, P.N. Burrows and G. Christian (2010). Luminosity performance studies of the compact linear collider with intra-train feedback system at the interaction point. *JINST* **5** P09007. doi:10.1088/1748-0221/5/09/P09007

3. A. Aryshev et al. [19 authors including B.Foster, R.Walczak and 7 others from Oxford] (2010). Micron size laser-wire system at the ATF extraction line, recent results and ATF-II upgrade. *Nucl. Instr. and Meth.* **A623**, 564. doi:10.1016/j.nima.2010.03.071

4. *G. Doucas, V. Blackmore, B. Ottewell, C. Perry, E. Castro-Camus, M.B. Johnston, J.L. Hughes, P.G. Huggard, M.F. Kimmitt, B. Redlich and A. van der Meer (2006). Longitudinal electron bunch profile diagnostics at 45-MeV using coherent Smith-Purcell radiation *Phys.Rev.ST Accel.Beams* **9** 092801. doi:10.1103/PhysRevSTAB.9.092801

5. *R. Bartolini, P. Kuske, F. Schmidt, I.P.S. Martin, J.H. Rowland (2008). Correction of multiple nonlinear resonances in storage rings. *Phys.Rev.ST Accel.Beams* **11** 104002. doi:10.1103/PhysRevSTAB.11.104002

4. Details of the impact *[A], [B] etc are references to corroborating sources listed in section 5.*

Public engagement in accelerator science

Accelerate! is an outreach show that has been delivered in the UK and Germany to over 7,700 schoolchildren, in most cases aged 11-18. The ideas were developed by Sheehy and Foster with advice from Emmanuel Tsesmelis (CERN and Visiting Professor at Oxford) and supported by an STFC Small Award for £7,898 (ST/G502047/1, 2008-10). Its aim is to engage children in the excitement of accelerator science, and to build on the public interest in the LHC to explain more everyday applications.

The show is structured around the principal elements of a particle accelerator: particles, energy, control, collision and detection. The show also emphasises that the minority of accelerators are designed for particle physics (e.g. the Large Hadron Collider and International Linear Collider) while the majority are for medicine, industry or research in other disciplines (e.g. Diamond). It thus not only relies on a fundamental understanding of challenges in accelerator science, but also draws on current projects in the JAI for both existing and future accelerators across a range of potential applications. For example, a real prototype of a 30 GHz RF cavity from the Compact Linear Collider project based at CERN is shown to illustrate continuing development in the field.

The show gives demonstrations that provide specific insights into accelerator science. For example, an interactive map of accelerators in UK (excluding industry) is used to locate the accelerator nearest to the venue, which is often found to be in a hospital; and a 'Mexican wave' transporting beach

balls through audience participation (original to this project) illustrates the acceleration of charged particles by a radiofrequency wave.

Primary audiences: attendees and benefits received

The first performances of *Accelerate!* were in December 2008. So far it has been performed by teams from Oxford Physics 76 times, in schools and elsewhere around the UK, to a total of over 5300 students, 280 teachers and 995 members of the public [A]. This includes sixteen performances at the British Science Festival in September 2010 to over 1000 students aged 11-14. Respondents to surveys held in some of the early shows (from 487 feedback forms from schoolchildren), agreed or strongly agreed with the following opinions [A]:

- 78% 'understood the science'
- 91% thought 'the presenters did a good job'
- 43% were 'interested in physics' and 33% 'not interested' before they saw the show
- 62% were 'more interested in physics now they've seen the show' and only 7.6% not

Wider uptake and sustainability

From the beginning*, Accelerate!* was designed to be presented predominantly by graduate student volunteers who pass on their expertise to more junior colleagues, thereby ensuring the continuation of the project and that the age difference to the audience is minimised. In 2012, Andrew Steele, also an Oxford Physics graduate student, developed some resources and training for new participants outside Oxford, supported by an award of £9,629 from STFC (ST/J501827/1) and £10,000 (including in-kind support) from the South East Physics Network, SEPnet. As a result, a 'toolkit' to allow others to put on their own versions was made available online, under a Creative Commons licence.

One of the demonstrations used in the show is a simple cloud chamber, adapted from a teachers' workshop at CERN. To enable others to include this in their own presentations, Sheehy and Steele made a video of its construction and demonstration that has had over 25,000 views on YouTube [B]. A podcast of an entire performance in Oxford has been downloaded approximately 200 times since February 2012.

The SEPnet group of universities now delivers *Accelerate!* under licence [C] and by February 2013 they had given 20 additional shows to over 1880 attendees. Foster founded a team at the DESY laboratory in Hamburg, Germany, to adapt the concepts of *Accelerate!* for their own show in German, known as *Rennmaschinen* [D], which attracted 560 children and 166 adults over its first seven performances (April 2012 – June 2013).

Benefits to teachers

Accelerate! has been performed specifically for teachers twice at a conference in York and once in Oxford, with a total audience of 130. Of the 103 survey responses received, 92 indicated they would recommend the show to other teachers and 87 considered it to be a good way to help students understand concepts in physics.

A training session for teachers by Sheehy, drawing on experience and demonstrations from *Accelerate!*, formed part of the annual Accelerator and Particle Physics Education at A-Level (APPEAL) one-day course in Oxford (2010-2013) in collaboration with CERN. Approximately 20 teachers attended each year. Comments received from participants in 2010 included,

> *"You have all inspired me to do some background reading and learn a little more."*
> *"I have been inspired to try to increase the prestige and attainment in Physics in my school through a trip to CERN."*

The 16 teachers who responded to online evaluation surveys in 2010 and 2012 considered they had gained a better understanding of particle physics and accelerators and that it would help their teaching at AS/A level [E]. Eleven teachers from 2010 and 2011 responded to a follow-up questionnaire in 2012: all reported that it had informed their teaching 'a great deal' or 'quite a lot', identifying 'up to date information' as one of the most useful aspects, and all but one had

undertaken some other follow-up activity [E]. The APPEAL course is now well established: APPEAL-4 was delivered in June 2013 and included a presentation by Sheehy on applications of particle accelerators. Sheehy's session was also incorporated in CERN's High School Teachers programme in 2010 (60 participants) [F].

External recognition and invitations

The John Adams Institute led a team, with a number of collaborative partners and sponsors, that successfully proposed and developed an exhibit for the prestigious Royal Society Summer Science Exhibition in 2009 [G]. This exhibit, '*Accelerators Everywhere: From the Big Bang to curing cancer*', emphasised the practical applications of accelerators and included hands-on activities informed by the experiences of *Accelerate!.* The exhibition as a whole was visited by over 4000 members of the public [H].

At the 2010 British Science Festival, Sheehy gave the 2010 Lord Kelvin Physical Sciences Award Lecture discussing the funding of international accelerator experiments and wrote a guest blog describing the *Accelerate!* show. Andrew Steele was invited to co-present for an episode of the 'How Do' series on ITV Meridian in 2010, answering the question "How do you make science fun?" using a number of *Accelerate!* demonstrations. The four annual finalists for the Institute of Physics' Very Early Career Physics Communicators Award have included both Sheehy in 2011 [I] and Steele in 2012.

Coverage on BBC Radio Oxford has widened the reach further. An interview about *Accelerate!* at the Cooper School, Bicester, for the Oxford Science Roadshow, was featured on 'Daytime with Danny and Lou' on 11th March 2009. In January 2010, the Breakfast show with Malcolm Boyden featured a 5 minute demonstration with explanations by Suzie Sheehy, Andrew Steele and Rosalind West (4 - 8th January 2010).

5. Sources to corroborate the impact

Impact on audiences in Oxford

A. Records of performances 2008-13 and evaluation data held on file in Oxford.

Reach beyond our own audiences:

B. Download statistics for video on cloud chamber: http://www.youtube.com/watch?v=400xfGmSlqQ&feature=feedu
C. SEPnet brochure advertising *Accelerate!* and acknowledging Oxford: http://www.astro.soton.ac.uk/~s.jones/SEPnetBooklet.pdf
D. *Accelerate!* as source of material for the DESY show: http://newsline.linearcollider.org/2012/08/16/physics-that-goes-bang/

Significance to teachers:

E. Evaluation data from APPEAL, held on file in Oxford
F. CERN HST agenda, 2010 http://indico.cern.ch/conferenceDisplay.py?confId=96344

External recognition of effectiveness of outreach:

G. Royal Society Summer Science Exhibition (RSSSE) 2009, 'Accelerators Everywhere', http://royalsociety.org/summer-science/2009/accelerators-everywhere/
H. RSSSE 2009 audience figures from the Royal Society: report held on file in Oxford
I. 2011 Very Early Career Physics Communicator Award: http://www.iop.org/activity/groups/subject/physcom/prize/file_55202.pdf