Fundamental Science Drives Innovation

Carsten P. Welsch

Contents

1	Fundamentals Science: For the Advancement of Humankind	126
2	Accelerating Society	128
3	Training the Next Generation	128
4	Summary and Outlook	132
	References	133

Listening to the words “fundamental science” many people often think that this concept refers to something distant from their daily lives; a fact that already poses a challenge when thinking who and how profits from investments in these fields.

It turns out though that fundamental research is interwoven with our everyday life. Today, there are more than 50,000 particle accelerators in the world [1], ranging from the linear accelerators used for cancer therapy in modern hospitals to the giant ‘atom-smashers’ at international particle physics laboratories used to unlock the secrets of creation. For many decades these scientific instruments have formed one of the main pillars of modern research across scientific disciplines and countries.

Many of today’s most advanced research infrastructures rely on the use of particle accelerators. This includes for example synchrotron-based light sources and Free Electron Lasers, high energy accelerators for particle physics experiments, such as the Large Hadron Collider (LHC), high intensity hadron accelerators for the generation of exotic beams and spallation sources, as well as much smaller accelerator facilities where cooled beams of specific (exotic) particles are provided for precision experiments and fundamental studies.

Much less known is the fact that particle accelerators are also very important for many commercial applications, such as for example medical applications, where they are used for the provision of radioactive isotopes, x-ray or particle beam

---

C. P. Welsch (✉)

Physics Department University of Liverpool and Cockcroft Institute, Liverpool, UK

e-mail: C.P.Welsch@liverpool.ac.uk

therapy. Furthermore, they are widely used for material studies and treatment, lithography, or security applications, such as scanners at airports or cargo stations.

This article first presents how accelerators enable scientific discoveries, before discussing some of the applications that now benefit our society on a daily basis. It closes by showing the unique training opportunities offered by this interdisciplinary field.

1 Fundamentals Science: For the Advancement of Humankind

Curiosity-driven fundamental research has driven revolutionary transformations of society, such as the rapid growth of computer-based intelligence and the discovery of the genetic basis of life. Albert Einstein's famous theory of relativity is now used every day as part of the Global Positioning System (GPS) and built into mobile phones and car navigation systems.

Fundamental research not only radically alters our understanding of the world around us, it also leads to new tools and techniques that transform society, such as the World Wide Web, originally developed by particle physicists at CERN to foster scientific collaboration. Cutting edge research requires the sharpest minds and needs them to work together on some of the hardest challenges. The outcomes of these collaborative studies then often have an earth-shattering impact on our everyday lives.

The path from exploratory fundamental research to society applications is, however, not direct nor is it predictable. Sometimes, new technologies enable even more fundamental discoveries, e.g. quantum mechanics, and these in turn are the basics for applications such as quantum computing which has huge potential to revolutionize the way we use computers altogether.

To use the full potential of human intellect and innovation, it is important to find a good balance between finding solutions to short-term problems and at the same time enabling real transformational studies that usually come from serendipitous discoveries [2].

Unfortunately, decreasing funding for research, combined with economic and political uncertainty, has led to a focus on short-term goals that often help address current problems. However, these risks miss the huge transformational discoveries that historically, almost always, arise from fundamental research.

Particle accelerators have been one of the driving forces behind scientific discoveries and, in turn, ground-breaking innovations. The need for higher-energy beams for fundamental research as compared to those found from natural radioactive sources has been the major motivation for advances in particle accelerators.

The LHC is currently the world's largest particle collider allowing the global particle physics community to explore nature at its most fundamental scales. It is hosted in a 27 km circumference tunnel beneath the France-Switzerland borders in the Geneva area. The LHC was built thanks to the collaboration of about 10,000 scientists and hundreds of universities and laboratories from more than 100 countries

Already in 1927, Lord Ernest Rutherford demanded a “copious supply” of projectiles with higher energies, as natural α and β particles would provide. When he opened his High Tension Laboratory, he stated that “we require an apparatus to give us a potential of the order of 10 million volts which can be safely accommodated in a reasonably sized room and operated by a few kilowatts of power. We require an exhausted tube capable of withstanding this voltage.” John Cockcroft and Ernest Walton picked up this specific challenge and invented the high-voltage generator that is now named after them.

Almost 100 years later, accelerators are still at the core of scientific discovery and enable research groups from around the world to work together on some of the biggest scientific challenges. The LHC has enabled the discovery of the Higgs Boson—the last missing piece in the Standard Model of Particle Physics—and scientists are currently planning to build an even better microscope to understand the building bricks of our universe even better. This will have to be done in a truly global effort, where generations of researchers work across disciplinary and country borders. “*Science knows no borders*”, said former CERN Director General Rolf Dieter Heuer in a recently produced film about the Future Circular Collider study [3].

2 Accelerating Society

Curiosity-driven research requires and drives innovation in the research techniques and technologies underpinning scientific studies. High(er) power magnets required for controlling the movement of ever-higher energy particle beams for example, readily find application in MRI scanners in hospitals or can help find honey launderers [4]. Innovations resulting from fundamental science studies usually also find application in other areas that benefit society in various ways. Particle accelerators are no exception to this.

Passengers at London's Heathrow Airport got some good news recently when it was announced that—thanks to the airport's new computerized tomography (CT) scanners—they will soon be able to stop separating out the liquids and gels in their hand luggage as they go through security. The new scanners produce high-resolution, three-dimensional X-ray images in real time, making it easier to detect explosives quickly, without the need for a separate screening process. This has been achieved, in part, by improvements to the accelerators that provide the electron beams for the scanners [5] and the image processing techniques. A clear example of progress that was made possible through advancement in technologies and tools which originally targeted fundamental research.

Another example of technology transfer in accelerator science relates to cancer treatment using proton and ion beams. This technique takes advantages from the so-called “Bragg peak”—the fact that protons when going through matter (i.e. a patient's body) do not pass all the way through the body. Instead, they stop sharply at a specific depth determined by their energy. By modulating the beam's energy and direction, one can deliver a specific treatment dose over a 3D tumour volume while sparing healthy surrounding tissue. An international R&D effort has focused on the development of novel beam and patient imaging techniques, studies into enhanced biological and physical simulation models using Monte Carlo codes, and research into facility design and optimization to ensure optimum patient treatment along with maximum efficiency [6]. Collaborative research within the Optimization of Medical Accelerators (OMA) project for example has helped improve cancer treatment using ion beams. Future studies will now look into making this technology more accessible and more abundant in number. Scientists and engineers will be working hard on reducing the entry costs for users in medical imaging, cancer treatment, security and materials science [2].

3 Training the Next Generation

Cutting-edge fundamental science requires our best scientific minds to calculate, observe, and invent together in a way that leads to the next innovation. This attracts scientists and engineers at an early stage and allows for high quality training that is increasingly cross-sector, interdisciplinary and international. International links,

research and knowledge exchange are all aspects that help enhance the education level of society—which in turn lets the economy prosper.

The design, construction, commissioning, operation and subsequent operation of accelerator-based research infrastructures requires researchers from many different disciplines including physics, engineering and computer sciences to work closely together. Despite the need for skilled experts in this area, there are very few universities in the world that offer structured courses on accelerator physics as part of their curriculum and often researchers have to be re-trained ‘on the job’ after their graduation to PhD in one of the above areas.

To overcome this gap in specific research skills training, the Innovative Training Network (ITN) scheme within the European Union’s Marie Skłodowska Curie (MSCA) has provided unique support to the accelerator community for more than 10 years and sets one of the best examples for maximizing the investments in fundamental research. The scheme supports competitively selected research networks which combine partnerships of universities, research institutions, research infrastructures, businesses, SMEs, and other socio-economic actors from different countries across Europe and beyond. Each ITN enables cutting edge R&D and provides network-wide training to its Fellows during the 4 year project duration. Any subject area can apply and the best ideas are selected in a bottom-up approach.

ITNs exploit complementary competences of the participating organisations, and enable sharing of knowledge, networking activities, the organisation of workshops and conferences to train their Fellows which are usually employed by different host institutions for 36 months. With a success rate of only 5–7%, the ITN scheme is amongst the most competitive funding schemes.

The University of Liverpool/Cockcroft Institute has been exceptionally successful in coordinating ITNs in accelerator science. These programs started in 2007 with DITANET, a research network focusing on R&D into advanced beam diagnostic techniques for particle accelerators and light sources [7] which was proposed to the physics panel within MSCA in Framework Program (FP) 7. The network was an enormous success: With a funding of €4.2 million it trained 22 Fellows (PhD students and Postdocs), organized 4 international schools with up to 100 participants, as well as 9 international workshops for 30–70 participants, as well as an outreach symposium and final conference on beam diagnostics for the world-wide accelerator community. Presentations from all events remain accessible via the project home page and continue to serve as a unique knowledge base for the accelerator research community.

Building up on the successful collaborative model of DITANET, two further ITNs started within FP7 in 2011: oPAC (Optimization of Particle Accelerators) which was submitted to the physics panel and received €6 million to train 23 Fellows [8], making it one of the largest ITNs ever funded, and LA3NET (Laser Applications at Accelerators), submitted to the engineering panel which received €4.6 million to train 19 Fellows [9]. The two networks ran in parallel and shared a number of training events and also stimulated researcher exchange programs.

Taking the oPAC approach further, but focusing on a more specific area within accelerator science, OMA (Optimization of Medical Accelerators) was evaluated by

the life science panel and was the first-ever ITN that received a 100% evaluation mark. OMA started 2016 to train 15 Fellows with a budget of €4 million and will run until the end of 2020 [10]. Finally, AVA (Accelerators Validating Antimatter research) started in 2017 and was selected by the physics panel to train 15 Fellows with a budget of again €4 million [11].

Group photo of AVA School on Antimatter Physics at CERN in Geneva, Switzerland. One of the MSCA ITN projects for next-generation of researchers that show a high multiplication factor for the impacts of investments in fundamental science

A structured combination of local and network-wide trainings is the central concept of all ITNs. Existing and well-proven training schemes are typically exploited, but at the same time novel training opportunities are made available which no single partner alone could offer. For example, hands-on training through research at accelerator facilities is a unique training opportunity which rarely can be provided within standard university doctoral programs.

With the exception of several Postdocs who were employed in DITANET (the option to employ Postdocs did no longer exist in later projects), most Fellows were registered for a PhD. This embeds them into a structured course program at their host university or, if their work contract is with an industry partner or a research center, with a collaborating university. Courses are selected at the start of their project in discussion with their supervisors, based on their project needs and their own background and reflected in their individual career development plan (CDP). In addition, network-wide trainings bring the Fellows together on a regular basis. This ensures that in addition to research-based overlap and links between projects,

interpersonal links between the Fellows are established. Most network-wide events also include external participation and hence efficiently link the Fellows to the wider scientific community.

Within higher education there has been a move to provide graduates with the skills and knowledge required in society, equipping them for the world of work, often referred to as the ‘skills agenda’. For example in the UK the development of transferable generic skills, in addition to those relating to subject disciplines, have been included in PhD research training [12]. However, such training is not formalized at many universities.

The ITNs mentioned above guarantee international competitiveness of the researchers trained within them by providing them with the necessary skills for a future career in either the academic sector or in industry. For that purpose, an interdisciplinary 5-day training program, designed for the particular needs of early stage researchers, is held in the first few months of each project at the University of Liverpool. This training is organized in collaboration with central university PGR teams, as well as key industry partners, including Fistrat Consulting, Holdsworth Associates and Inventya. It consists of a ‘project specific’ part and a part addressing more ‘general skills’, which are based on group work.

This school programme was developed and tested during DITANET and has since been adopted as standard for all first year postgraduate students in the School of Physical Sciences at the University of Liverpool. This approach was praised during mid-term reviews of DITANET, oPAC and LA3NET and acknowledged as one of the ‘best practices’ in Europe. A final year advanced researcher skills training complements the general training. It focuses on the next career step and includes sessions on CV writing, interview skills, international networking, grant writing opportunities, technology transfer, and international career avenues for researchers.

In terms of the scientific training, each ITN usually organizes at least two international schools in their core R&D areas. These events are open to 70–100 participants and all course materials remain available via the respective webpages, which can be easily accessed through the project home page.

In addition, the networks have already organized dozens of targeted scientific workshops at venues across Europe, and there are many more in the planning. Each workshop lasts 2–3 days, is open for network members, as well as external participants, and focuses on expert topics within the respective network’s scientific work packages.

Finally, towards the end of a project cycle, a network typically also organizes an international conference. These conferences include sessions on all R&D aspects within the respective network and highlight the research outcomes. Following the example of DITANET, oPAC and LA3NET joined forces and organized an international Symposium on Lasers and Accelerators for Science & Society took place on 26 June 2015 in the Liverpool Arena Convention Centre. With speakers including Professors Brian Cox (Manchester University), Grahame Blair (STFC), and Victor Malka (CNRS), the event was a sell-out with delegates comprising 100 researchers from across Europe and 150 local A-level students and teachers.

More recently, a joint Symposium on Accelerators for Science and Society between OMA and AVA, as well as the UK Centre for Doctoral Training on Big Data Science LIV.DAT [13] has copied this approach and was held at the Liverpool ACC in June 2019. It was preceded in March 2019, by another successful symposium “Particle Colliders—Accelerate Innovation” organized in Liverpool’s Arena with the support of CERN and the EU-funded EuroCirCol project [14] accompanied by an Industry Innovation Workshop.

Thus far, almost 100 early stage researchers have been trained within MSCA networks coordinated by the author of this paper in the field of accelerator science, and probably hundred more through other networks. They have produced remarkable research results and trained an entire new generation of accelerator experts. Further collaborative projects on this basis have already emerged and have driven science and technology in this field. The training approach behind these initiatives has impacted very significantly on the world-wide accelerator community where several thousand researchers have already participated in one or several of the international schools, workshops and conferences. It has also served as an example for postgraduate training schemes outside of accelerator science and was commended as “best practice” by the EU as part of several formal project reviews.

The career development of fellows who were part of previous ITNs has been exceptionally good. This is certainly due to the high quality of researchers who were recruited in the first place, but their feedback has clearly indicated that the training, international networks, and cross-sector experiences they had access to, has boosted their skills and career prospects.

Despite such a considerable number of experts already trained in accelerator science, there remains a shortage of experts to drive R&D in accelerator science. Future initiatives will base their training model on the ideas presented in this paper as this has proven to provide maximum benefit for the Fellows, the R&D projects, and the institutions involved.

4 Summary and Outlook

R&D into particle accelerators has been driving innovation for more than 100 years. This has resulted in break-through scientific discoveries and enabled applications with enormous benefits for society. In the twenty-first century we clearly see a shift towards collaborative-driven research as discussed in the above examples.

This structural change in the way science is done should inform our thinking on how to improve the societal benefits from fundamental research and when designing future research infrastructures—that should facilitate and enable similar networks. Fundamental research provides a fruitful ground for training the next generation of researchers. Secure funding and opportunities for continued exchange of researchers and knowledge are needed to ensure an even brighter future.

Acknowledgement Research reported in this article has received funding from the European Union's FP7 and Horizon 2020 research and innovation programmes under Marie Skłodowska-Curie grant agreement Nos 215080, 289485, 675265 and the INFRADEV-1-2014-1 call under grant agreement 654305.

References

1. L. Rivkin, Plenary ECFA meeting, CERN (2018), <https://bit.ly/2CuGm9a>
2. N. Smith, "The biggest surprises always came from serendipitous discoveries", E & T magazine 14(9), 2019, <https://bit.ly/34HQp6l>
3. Science knows no borders, <https://youtu.be/3pPAcrLUGX0>
4. Busy bees and mighty magnets, <https://youtu.be/IGImJmwiXo>
5. C.P. Welsch, "What have particle accelerators ever done for us?", Physics World (2019), <https://bit.ly/2NxCRVE>
6. Optimization of Medical Accelerators project, online brochure (2019), <https://www.liverpool.ac.uk/oma-project/brochure/>
7. DITANET, <http://www.liv.ac.uk/ditanet>
8. oPAC, <http://www.opac-project.eu>
9. LA3NET, <http://www.la3net.eu>
10. OMA, <http://www.oma-project.eu>
11. AVA, <http://www.ava-project.eu>
12. G. Wall, C.P. Welsch, "Employability in Europe: enhancing postgraduate complementary skills training", Proceeding of HEA STEM Learning and Teaching Conference Series, Birmingham, UK (2013).
13. LIV.DAT, <http://www.livdat.org>
14. <https://indico.cern.ch/event/747618/timetable/?view=standard>

Open Access This chapter is licensed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.