

In March this year, hundreds of researchers and companies from across Europe, as well as university students and school children, came together to discuss the technologies being developed within the global Future Circular Collider (FCC) study.

The symposium - "Particle Colliders – Accelerating Innovation" - was co-hosted by the University of Liverpool and CERN, along with partners from the FCC and EuroCirCol projects, and looked to investigate the opportunities that next generation colliders could offer to industry, science and society.

Two months prior to this, CERN published its conceptual design report for the FCC, a potential successor to the Large Hadron Collider (LHC), which aims to be four times larger and seven times more powerful.

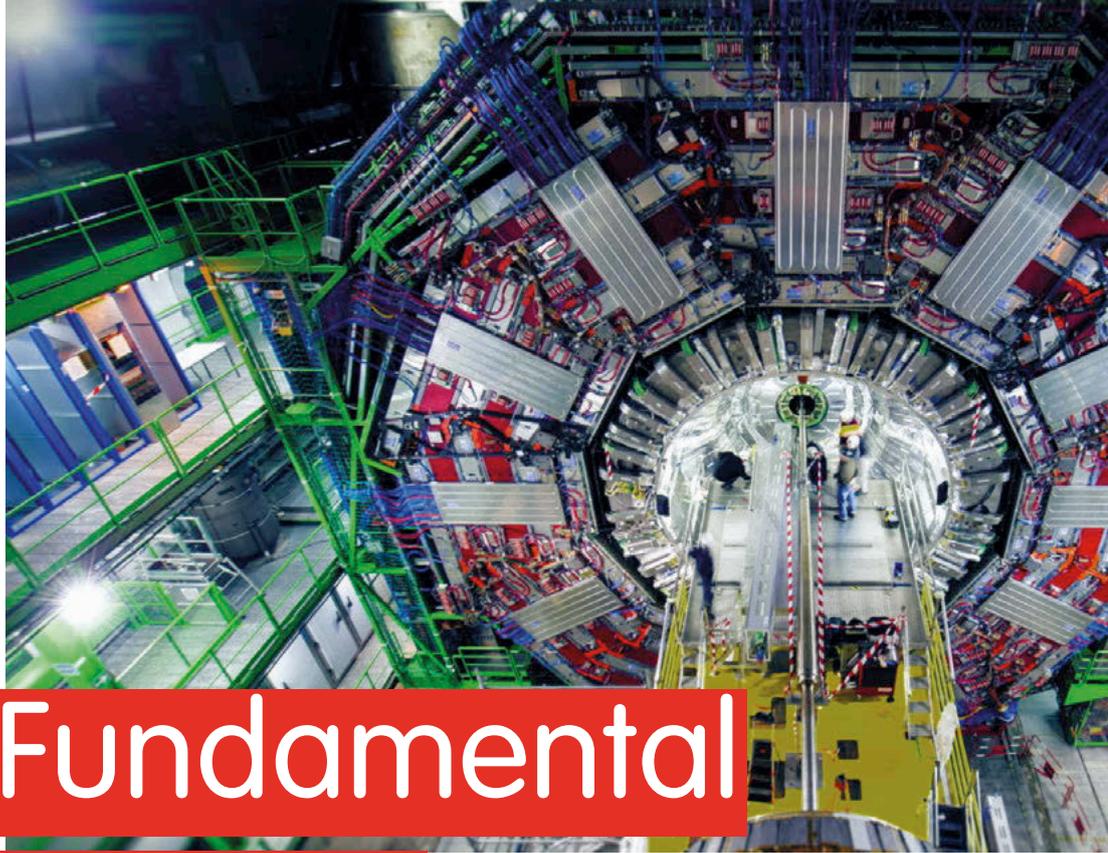
The fundamental science at the heart of this project not only pushes the boundaries of science but looks to benefit society, not only by generating knowledge but by creating unexpected and transformative applications.

Particle accelerators are at the heart of many of the most advanced research infrastructures and have led to the development of innovative technologies that have fundamentally changed peoples' lives - whether through advances in medical imaging or the creation of the World Wide Web.

Particle accelerators are expected to have an even greater impact on science and society in the future and, according to Professor Carsten Welsch, Head of the University of Liverpool Physics Department, they should be seen as our generation's equivalent of space exploration.

"They have the potential to change the world and improve our understanding of the fundamental building blocks and forces that make up our universe," he argues.

"Developing the design concept for future research infrastructures is not just about the science they would enable; it also requires us to drive technological progress that will benefit our everyday lives."



# Fundamental Science

How fundamental science research is helping to transform the world around us. By **Neil Tyler**

Strengthening links between industry and academia, to pave the way for future collaborative projects, is critical for further advances in areas as diverse as cryogenics and superconducting magnets.

"Innovations derived from fundamental research have had many positive impacts beyond the laboratory," according to Amy Bilton, Knowledge Transfer Officer, CERN.

"The aerospace industry has benefitted from CERN's unique radiation testing facilities, for example, and several CubeSat systems were tested in CHARM (CERN's high energy accelerator mixed-field facility) to compare ground and flight radiation data."

One company attending the event in Liverpool, and an example of the synergies between fundamental research and the development of applications, is Oxford-based Adaptix, a partner in the pan-European research and training network OMA (Optimization of Medical Accelerators).

Working on laser-driven particle accelerators at UCLA (in Los Angeles), the company's co-founder Dr Gil

Above: The Future Circular Collider (FCC) is intended to replace the Large Hadron Collider, and aims to be four times larger and seven times more powerful.

Travish saw the potential to use the emitter arrays he had developed in 'gene-chips', to help in the search for DNA unravelling and is now bringing a product to market.

According to Dr Travish, "It was encouraging to see how a concept born out of the pursuit of basic research could then be adapted to a very applied field."

## Conceptual design report

CERN's conceptual design report for the FCC said that its objective would be to find new particles and offer a better understanding of the rules that 'govern the universe'.

A particle accelerator uses electromagnetic fields to propel charged particles to very high speeds and energies and contain them within controlled beams.

The LHC is the world's most powerful accelerator and can accelerate two beams of protons to an energy of 6.5 TeV and cause them to collide head-on, creating centre-of-mass energies of 14 TeV.

To achieve higher energies a longer tunnel is needed and while the LHC



runs to 27km, its successor will have a circumference of 80-100km, offering a centre-of-mass energy of the order of 100 TeV.

Crucially, the FCC is not just about progressing science but providing a well-controlled environment, a test-bed, to enable the development of technologies under conditions that extend well beyond conventional product requirements.

Industry partners will have access to an extensive academic community, in fact many of the companies that have benefited to date from involvement with the LHC have been SMEs. Through a number of successful collaborations, these small businesses have brought technologies to maturity, creating improved products and generating new markets.

Among the examples of technologies that have come out of work conducted at LHC are chip development in mobile devices, 3D scanners, 3D coloured X-rays, radiation monitoring in adverse environments, robotics, data communications and cryogenics.

The impact of the work carried out has been profound. In fact, 1400 firms in 30 countries have collaborated at the LHC and 25 companies are now involved in the first stage of the FCC.

Ross Robotics developed a

robotic modular platform that can be re-configured to perform a variety of different tasks using a broad range of sensors and tools.

The platform was tested and used in CERN and was able to show that it could cope with very hostile conditions, from strong magnetic fields to transient radiation levels.

Another company, Medipix, developed a spectral imaging chip for a medical scanner derived from technology used by particle physicists at CERN, and which provides 3D colour x-rays to help consultants spot and then treat diseases without the need for surgery.

“Medipix’s technology is also being applied in the field of art restoration and is used for monitoring radiation levels in the International Space Station,” says Bilton.

Beyond these specific examples, though, a large-scale accelerator controlled and monitored by thousands of sensors and actuators actually provides a suitable test-bed for the technologies that are supporting Industry 4.0.

The smart factory requires the support of a cyber-physical system (CPS) that can act largely autonomously, continuously interacting with its environment and controlled by efficient embedded software.

But beyond that, some of the applications for CPSs also include consumer electronics, traffic control and critical infrastructure control.

#### **FCC collaboration**

According to Professor Welsch, to be able to reach the higher energy levels required by the FCC, high-energy electric fields will be needed to speed up the particles.

“The particles would need to be constrained to form beams that will bend in a circular trajectory,” he explains. “This would be achieved through the use of superconducting magnets, cooled to very low temperatures using large-scale cryogenic systems. Current magnetic

fields in the LHC reach 8 Tesla; the new magnets will need to reach up to 16 Tesla.”

The knowledge as how to build these high-field magnets does not yet exist, so forms part of the FCC study.

“It is anticipated that the challenges associated with the FCC will drive innovation in areas such as precision mechanics, surface treatment, superconductivity and novel materials.

“Modelling and testing in extreme environments have wider applications, and advances in our understanding of the universe will come from measuring the physical phenomena with higher precision and comparing this to theoretical predictions,” explains Prof. Welsch.

The most advanced detector systems currently available are complex assemblies designed to record 4-dimensional data from a continuous stream of collisions, forty million times a second.

The FCC will require different approaches to achieve the ideal detector – one that offers infinite precision with zero mass.

“By aiming at this seemingly impossible goal the advances in technology will have spinoff benefits for less exacting applications,” says Prof. Welsch. “Improved techniques for particle detection, beam optimisation and monitoring have much wider applications.”

Advances in finite-element modelling and computational fluid dynamics are enabling the generation and acceleration of particles to be investigated in detail, but because the particle sources are complex and exhibit numerous emergent behaviours these cannot be predicted by simulation alone.

“Therefore, development rigs that replicate the actual environment and are equipped with diagnostics are essential,” says the professor.

To accelerate particles, the accelerators have to be fitted with metallic chambers containing an



**“Particle accelerators have the potential to change the world and our understanding of the fundamental building blocks that make up our universe.”**

Prof. Welsch

electromagnetic field known as radiofrequency (RF) cavities. Charged particles injected into this field receive an electrical impulse that accelerates them.

“There are currently two main technologies: bulk niobium (Nb), which is widely used; and thin superconducting film coated cavities, which are only available in large laboratories,” explains Prof Welsch.

“Coated cavities are the subject of research and have huge potential for improving the efficiency and lowering the cost of accelerators.

“The LHC uses sputtered Nb on a copper cavity, technology which has been transferred to industry and now offers an alternative to bulk Nb and superfluid He cooling for applications that require low frequencies and 4.5K operation.

“As the RF current only penetrates a layer of a few hundred nanometres, films offer the potential to decouple the functions of the superconducting surface from the substrate.

“This creates the opportunity to large scale manufacture cavities in high thermal conductivity materials coated in a thin film of superconducting film. This would require developments in surface finishing and techniques for depositing high quality films on complex surfaces.”

### Superconducting magnets

Before reaching the LHC particles pass through a series of smaller accelerators, and as they reach the maximum speed each accelerator can achieve, they are shot into the next. Without other forces involved the momentum of the particle would carry them in a straight line so 50 types of magnet are used to send them along complex paths without losing speed.

“Improving the efficiency of magnets through advances in mechanical design, electrical insulation, and quench protection would ease the demands on cryogenic systems, leading to increased stability

and lower cost,” according to Prof Welsch. “Currently an increase in a magnetic field by a factor of 2 to 3 can significantly reduce the performance of ion sources and accelerators for the production of radionuclides and ion therapy.

“Producing reliable field strengths and qualities beyond 10 Tesla creates the opportunity for affordable and compact Nuclear Magnetic Resonance (NMR) analysis.”

NMR spectrometry is used to determine the structure of organic molecules, crystals and non-crystalline materials and in medical imaging techniques.

The magnets in the LHC are made with coils of a superconducting material called Niobium-titanium (NbTi), but this material can't support the high magnetic fields needed for the FCC, so new superconductors are being investigated.

The FCC aims to achieve a sustained field of up to 16 Tesla based on Nb<sub>3</sub>Sn LTS conductors operating at temperatures higher than superfluid Helium. However, this material is very brittle, making the production of coils with it difficult, so new processing techniques are also being investigated.

Particle accelerators operating at the high energy frontier result in costly electricity bills and large heat rejection. To improve efficiencies, the relationship between beam parameters and performance needs to be determined and extrapolated to define efficiency estimators – distinguishing intrinsic factors resulting from beam physics to those that depend on acceleratory technology and infrastructure.

“This can underpin strategies to improve efficiencies that can be implemented through technology developments and improved energy management processes,” explains the professor. “The collider tunnel contains two adjacent parallel beamlines, which travel in opposite directions around the ring. The beams



Above: The LHC runs to 27km, its successor will have a circumference of 80-100km.

intersect at four points around the ring, which is where the particle collisions take place.

### Novel materials

The investigation of novel materials, their behaviour and large-scale industrial applicability are essential for the beam-screen and beam-pipe system of the FCC.

“An example of this is Non Evaporable Getter (NEG) materials, which may lead to a successful transfer of fundamentally new technology to the market such as highly efficient solar panels; amorphous carbon with potential applications for powering systems at high frequencies and on-board radiofrequency systems for satellites; and molybdenum-carbide-graphite composites for use in aircraft design.”

The research and investment required to develop the FCC will also help to stimulate the development of embedded and real-time computing devices and improved tools for data management and storage.

By addressing the issues of reliability, availability, maintenance, support and safety of CPSs within the FCC, researchers will have the tools to then build a more reliable and energy efficient infrastructure.

The impact will also extend to civil engineering. The idea of tunnelling under the Alps to house the FCC is extremely ambitious. That to will require advances in tunnelling technologies to develop novel methods for online material analysis and separation to enable recovery and re-use of excavation materials and will involve material scientists, geologists and chemists.

The FCC certainly offers extraordinary opportunities for industry in terms of a better understanding of fundamental science, but also in pushing the limits of technology further and providing exceptional training for a new generation of technologists as they look to deliver new applications and devices.

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Amy Bilton