Accelerate to the next level

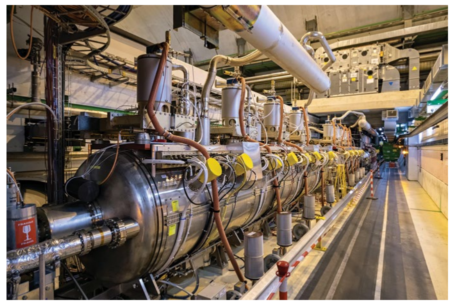
The merits of conventional particle accelerators range from fundamental science to applications like radiotherapy. Plasma-based accelerators are getting up to speed and may overtake conventional ones in the near future.

From old-school cathode ray tube televisions to state-of-the-art synchrotrons, particle accelerators have long conquered the world. Without accelerators, would humankind have discovered the Higgs boson, imaged how the smallest blood vessels in the lung are affected by the SARS-CoV-2 virus or studied rare isotopes with accelerator mass spectrometers? We cannot possibly know the answers to these questions, but what we do know is that our world would certainly look very different if the accelerator had not been invented in the 1930s.

In contrast to the electrostatic Cockcroft–Walton and Van de Graaff accelerators, most machines in use today rely on dynamic electromagnetic fields to accelerate particles. An early example was the betatron in which particles are accelerated through the electric fields induced by a time-varying magnetic field. But eventually, radiofrequency acceleration came out on top, where the field in a cavity oscillates at a given frequency. By timing the arrival of the particle, it experiences an accelerating field. Any particle that does not arrive at the right time will either be accelerated or decelerated, and thus particles are 'sorted' in bunches.

At the Large Hadron Collider (LHC) at CERN, sixteen radiofrequency cavities (pictured) are responsible for bringing, for example, protons up to speed: the injected proton beams with an energy of 450 GeV pass through the cavities more than ten million times before they reach the collision energy of currently up to 6.5 TeV (ref. [1]). Using proton–proton collision data recorded in 2011, 2012 and 2015–2018 at centre-of-mass energies of 7, 8 and 13 TeV, respectively, the LHCb Collaboration now presents a prime example of how accelerators advance our fundamental understanding of particle physics in this issue[2].

In the standard model of particle physics, the electron, muon and tau lepton couple with the same strength to the electroweak interaction. Previous measurements of decays of hadrons containing a bottom quark have, however, revealed hints that this principle of lepton flavour universality might be violated. Now, the LHCb Collaboration reports evidence for this



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violation with a significance of 3.1 standard deviations[2], which — if confirmed by future measurements — would be a clear indication for physics beyond the standard model, such as a yet unknown fundamental interaction between quarks and leptons.

Apart from their importance for fundamental research, accelerators also have many practical uses. Synchrotron light sources provide brilliant X-rays for, among other things, the structural analysis or the mapping of the chemical composition of materials or studying the coordination structure of atoms in complex biomolecules. The fabrication process of semiconducting devices uses accelerated ion beams, for example, to implement dopants into a solid target wafer, thus creating regions of tailored conductivity. Another important use is particle beam therapy — a form of radiotherapy — where certain types of tumours are irradiated with particle beams, such as protons or carbon ions.

One limitation of such therapies is the availability of a suitable accelerator, which also increases the cost of treatment. Out of the estimated over 30,000 accelerators worldwide, not all are suitable for medical purposes, and fewer than one per cent have a proton or heavy ion beam therapy centre associated with it — and the majority of them are located in the United States, Western Europe and Japan. In order to make particle beam therapy more cost effective and more accessible, smaller compact accelerator systems are therefore under development.

In this regard, laser–plasma accelerators are one promising route. Due to their high acceleration gradients, they can be built in a much more compact manner than conventional accelerators, leading to reduced costs. And relying on lasers, these accelerators have the potential to be distributed more widely and more equitably.

However, compared to established acceleration concepts, laser–plasma accelerators are still under development and their readiness for applications has yet to be established. Only recently, a proof-of-principle demonstration of free-electron lasing using a laser–plasma accelerator was reported[3], which paves the way towards their use as light sources. Another example illustrating how laser–plasma accelerators pick up the pace towards practical applications is part of this issue: Florian Kroll and colleagues report a step towards the clinical use of laser–plasma accelerators[4].

In their pilot study, Kroll and co-workers irradiated human tumours grown on mouse ears with a laser-accelerated proton beam, demonstrating the readiness of a laser-driven proton research platform for translational research. In the News & Views accompanying the Article, Leonida A. Gizzi and Maria Grazia Andreassi discuss the promise of laser–plasma accelerators in delivering ultra-high dose rates, which are believed to diminish the effects of the irradiation on the healthy tissue surrounding the tumour[5].

Accelerators have already had a huge effect on fundamental science and they have a myriad of practical applications. But as these recent developments show, alternative accelerator concepts also have great potential to unlock even more doors to fundamental insights and practical uses in the future. ❒

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