Accelerator physics

Muon colliders come a step closer

Robert D. Ryne

Particle colliders that use elementary particles called muons could outperform conventional colliders, while requiring much smaller facilities. Muon cooling, a milestone on the road to these muon colliders, has now been achieved. **See p.53**

"SMASH! Colossal colliders are unlocking the secrets of the universe." The cover story of the 16 April 1990 issue of *Time* magazine discussed giant particle accelerators, including the Superconducting Super Collider in Texas, which was ultimately judged to be too expensive for completion. Researchers at CERN, Europe's particle-physics laboratory near Geneva, Switzerland, went on to construct the Large Hadron Collider (LHC) in an existing tunnel. The LHC and other accelerators have been responsible for many major discoveries, but these "colossal colliders" have become colossally costly. Innovative approaches will thus be required to reduce the expense of future colliders in the search for previously unseen particles and physics phenomena. On page 53, the Muon Ionization Cooling Experiment (MICE) collaboration[1] reports results that bring scientists a step closer to realizing one of these innovative approaches: a muon collider.

Muons, like electrons, are elementary particles in the standard model of particle physics, but they have about 200 times the mass of electrons (go.nature.com/3twyjba). This fact has ramifications for the size, and therefore cost, of colliders, and for the energy that can be reached in their particle collisions (and thus their potential for discovery).

Although the goal is to accelerate particles so that they collide at the highest possible energies, the particles actually lose energy through radiation when their trajectories are bent by accelerator magnets. Heavy particles such as protons and muons lose much less energy than do lightweight particles such as electrons. For this reason, the circular colliders that can reach the highest energies (for example, the LHC) use protons. However, protons are not elementary particles. They are made up of elementary particles called quarks, and because the collisions are between bound quarks, only about one-sixth to one-tenth of the energy from proton collisions is available to produce other particles[2]. By contrast, because muons are elementary particles, all of the energy from their collisions is available for particle production.

Muon accelerators would have uses beyond those for particle colliders. For example, a 'Higgs factory' is a highly desirable facility that would produce huge numbers of elementary particles known as Higgs bosons and allow the properties of these particles to be precisely determined. A Higgs factory based on a conventional linear accelerator that collides electrons and positrons (the antiparticles of electrons) would have to be 10–20 kilometres long[3]. But one based on a circular muon collider would require a circumference of only about 0.3 km (ref. 4). In another example, if muons could be stored in a racetrack configuration that has long, straight sections, the decay of the muons in these sections would produce intense neutrino beams. Such a facility, called a neutrino factory, would shed light on the mysteries of neutrinos and on physics beyond the standard model.

Before a neutrino factory or a muon collider can exist, scientists must learn how to manipulate muon beams. Unlike electron beams, which are produced with almost laser-like quality, muon beams are generated through a complicated process resulting in a beam that is more reminiscent of the spray of pellets from a shotgun. This spray needs to be converted into a laser-like beam.

Such a conversion involves reducing the spread of the muons' positions and velocities in the directions perpendicular to the beam. A temperature can be associated with this spread, and cooling the beam decreases the spread. Several cooling techniques are used at accelerators, but none is fast enough to cool muons, which are unstable and short-lived.

Instead, a method called ionization cooling has been proposed for cooling muon beams[5,6], although it has never been used. In this approach, muons travel through an accelerator, a portion of which contains a material of low atomic mass, and the spread of the muons' positions and velocities is reduced as the particles ionize atomic electrons in the material. The MICE collaboration's aim was to build and test a system for the ionization cooling of muons, to demonstrate this cooling for the first time and to validate simulation tools for the design of ionization-cooling systems.

In the authors' experiment, a proton beam from the ISIS accelerator at the Rutherford Appleton Laboratory near Didcot, UK, struck a target to produce secondary particles (Fig. 1). Some of these particles decayed into muons, which were directed into an experimental apparatus consisting of focusing magnets, beam instrumentation and a cooling section that contained an energy-absorbing medium made of lithium hydride or liquid hydrogen.

Accelerator experiments usually measure the basic properties of a beam, such as its centre of mass, its spread in particle positions or its density profile. To demonstrate ionization cooling, the MICE collaboration took the unprecedented step of using the technology

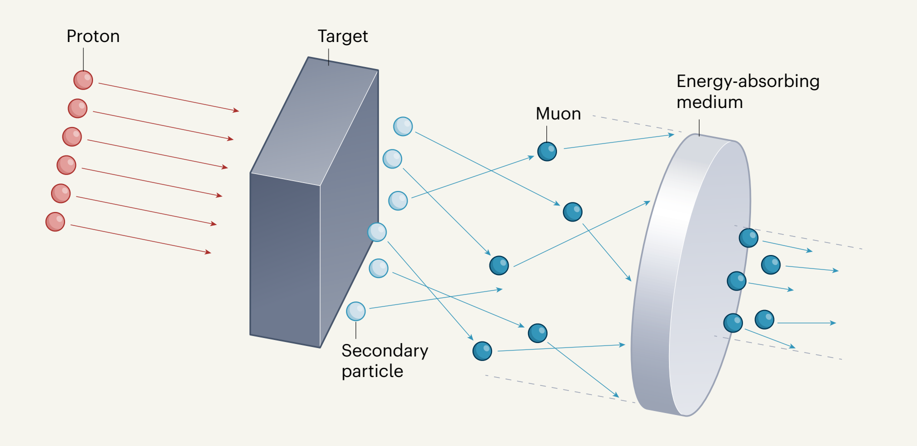

Figure 1 | Production and ionization cooling of muons. The MICE collaboration[1] carried out an experiment in which a beam of protons was directed at a target to generate secondary particles. Some of these particles decayed into elementary particles known as muons. The positions and velocities of the muons in the resulting beam had a wide spread (indicated by the dashed lines) in the directions perpendicular to the beam. Finally, the muons passed through an energy-absorbing medium made of lithium hydride or liquid hydrogen that reduced this spread by a process called ionization cooling. The process demonstrated by the authors could someday lead to a muon-based particle accelerator.

of collider detectors to measure both the input and output coordinates and velocities of every individual muon that passed through the experimental apparatus. As a result, the authors could unequivocally demonstrate that they had achieved ionization cooling of muons.

Organizations worldwide are developing long-term strategies for exploring the high-energy frontier. Plans include designs for circular colliders up to 100 km in circumference and linear colliders up to 50 km long[7]. Although these approaches, which would use protons or electrons and positrons, have the least technical risk, they still have a substantial cost, as well as technical challenges, that affect their feasibility.

Other plans include designs that would use innovative technologies such as those based on lasers and plasmas[8]. These approaches have made great progress in developing compact accelerator stages at low energy, but the combined use of such stages to reach high energies while retaining a high beam quality will require many years of research and development. Still other plans involve muon beams[9].

Thanks to the MICE collaboration, the first demonstration of ionization cooling of muons has been achieved. However, it must be noted that the amount of cooling was small. Although conceptual designs for muon colliders have been developed[9], establishing the viability of a realistic muon-cooling system and of a muon collider will need much more work.

It is too soon to say which, if any, of the proposed approaches will provide a technically and financially feasible path to the future energy frontier. But if physicists can learn how to cool and control muon beams, then it is hard to imagine that putting muons in a circular collider will not be the way forward. These particles offer clean collisions (unlike protons) and lose little energy when their trajectories are bent by accelerator magnets (unlike electrons). As a result, a muon collider could reach energies that match or surpass those of an electron or proton collider, but be substantially smaller. The MICE collaboration's work is a milestone on the road to realistic muon-cooling systems that could someday lead to neutrino factories and muon colliders.

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Climate science

Early models successfully predicted global warming

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Climate models published between 1970 and 2007 provided accurate forecasts of subsequently observed global surface warming. This finding shows the value of using global observations to vet climate models as the planet warms.

Climate models are equations that describe climatically relevant processes and are solved on supercomputers. In addition to being invaluable tools for testing scientific hypotheses, these models have long provided societally important forecasts. The first climate models to numerically describe an evolving and interacting atmosphere, ocean and land surface on a grid covering the entire Earth date back to the 1970s (for example, refs 1–3). Since then, the planet's surface has warmed, in large part because of increased emissions of greenhouse gases. Writing in *Geophysical Research Letters*, Hausfather *et al.*[4] retrospectively assessed the forecasting skill of climate models published between 1970 and 2007. Their results show that the physics in these early models was accurate in predicting subsequently observed global surface warming.

A key point emphasized by the authors is that the forecasting ability of climate models is limited by unknowable future climate drivers. Many major drivers, such as increased concentrations of carbon dioxide in the atmosphere caused by the burning of fossil fuels, result from human activities and decisions. Early climate modellers included estimates for future climate drivers in their forecasts. However, they could not know, for example, how the world would industrialize or the associated

Figure 1 | A Univac 1108 computer, from 1972. Hausfather *et al.*[4] demonstrate that climate models published over the past five decades accurately predicted subsequently observed changes in Earth's global mean surface temperature. These models include ones reported in the 1970s that used supercomputers, such as the Univac 1108, that had extremely limited power relative to those used today.

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