iThemba LABS

Magnetism in accelerator-based science

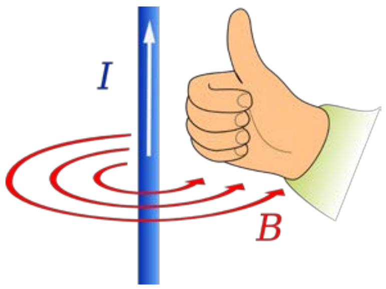
Gillian Arendse reports on the relevance of magnetism at iThemba LABS

At iThemba LABS, which stands for Laboratory for Accelerator Based Sciences, we make small things go *very* fast using strong magnetic fields. The research done at iThemba LABS uses beams of charged particles to study the origin of matter, but also to understand the interaction between radiation (energy as particles or waves) and biological systems. Apart from research activities, we also produce nuclear medicine such as radiopharmaceuticals to diagnose and treat cancer. Magnets and magnetic fields are used in a variety of ways here, but let's focus on three aspects:

- How we produce magnetic fields
- The role played by magnetic fields in the acceleration of charged particles
- How magnetic fields are used to help us 'see' the sub-atomic world and conduct research.

Producing magnetic fields

If you have ever been close to a powerline whilst listening to AM-radio and your radio went crazy, that was the magnetic fields created by the powerlines interfering with your reception. In electromagnetism lessons at school we learn the right-hand rule, which helps us understand that if we point our thumb in the direction of current flow, the magnetic field is indicated by the curl of our fingers. We use this principle at iThemba LABS by designing coils that will produce a magnetic field meeting our requirements when current (or electricity) is passed through them. The effect of the field can be enhanced by wrapping the coil around iron, also known as an iron yoke – rather like those school experiments to make an electromagnet by coiling wire around a nail and then connecting it to a battery for a current!



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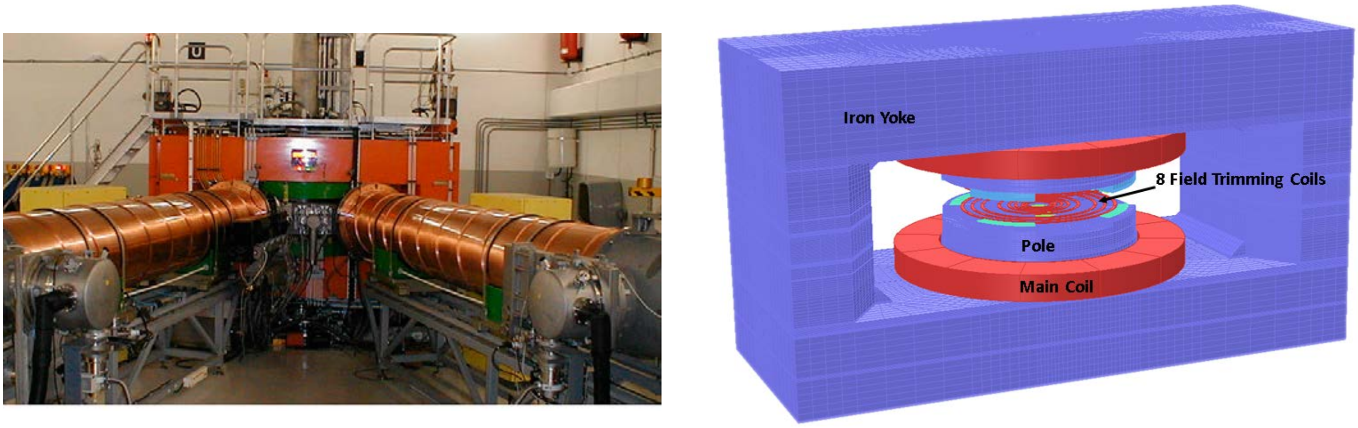
The right-hand rule states that our fingers show the direction of the magnetic field (B) when we point our thumb in the direction of current flow (I).

Accelerating particles

The charged particles used in accelerators are either protons, electrons or ions. The most common isotope of



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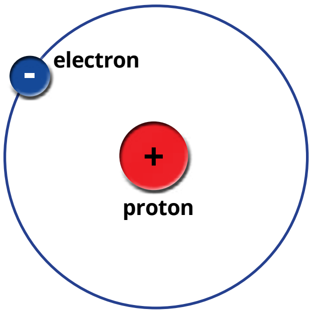
The green parts of this injector cyclotron are the coils, depicted in red on the schematic.



Hydrogen atom

hydrogen is the simplest of all atoms, consisting only of a proton in the nucleus and an electron. So, all we need to do is remove the electron through a process called ionisation, and we are left with the proton, a positively charged particle.

A charged particle experiences a force when it is exposed to an electric field. The direction of the force will be in the direction of the field if the charge is positive and opposite if the charge is negative. This means that electric fields can be used to make the charged particles go faster or slower. Dr Muneer Sakildien, representing Accelerator Operation and Technical Support at iThemba LABS, explains that the simplest version of an accelerator is a linear accelerator, the so-called LINAC, which accelerates charges in a straight line. The oldest (and biggest) accelerator at iThemba LABS is the Separated Sector Cyclotron, usually just called the SSC. A cyclotron accelerates particles in a circular manner, with the radius of acceleration linked to the speed at which the particle travels. This is much like a roundabout, where the distance from the axle determines how fast you travel.

At the heart of the circular motion is the interaction between moving charged particles and magnetic fields. The force exerted by a magnetic field on a charged particle is always perpendicular to the plane defined by the magnetic field and the motion of travel. This implies that a magnetic field can change the direction of travel, but it cannot accelerate the particle. That's where the electric field comes in. The electric field makes the particle go faster whilst the magnetic field changes its direction so that it keeps travelling in a circle. The SSC is capable of accelerating a proton to a maximum kinetic energy of 200 MeV (megaelectron volts). A proton with that amount of energy is able to travel a distance equivalent to four times around the Earth in one second!

In addition to their involvement in the acceleration of charged particles, magnetic fields are crucial in steering or bending and changing the profile of the beam. The beam of particles can be focused through the introduction of magnetic fields. The basic idea is that in much the same way we use lenses to focus light, we can use magnetic fields to confine the space within which the charged particles travel. The acceleration and delivery of the accelerated particle beams to the end-user forms part of the activities of the Accelerator Operation and Technical Support Department.

Using magnetic fields for research

When walking late at night we need a flashlight, or torch. The flashlight beam sheds light on objects and the reflected light is detected by our eyes, making it possible to see. This is essentially what scientists at iThemba LABS do when they conduct research. They use a beam of fast-moving particles (the probe) to illuminate a target, and a detector to see. The choice of probe, target and detector is informed by the specific study that is undertaken.

Dr Retief Neveling is one of our research scientists who works in the field of sub-atomic physics, and uses a magnetic spectrometer as his detector of choice.

Let's think about the basic process for a bit. How do you determine what is inside a gift-wrapped box without opening the box? You could shake it and listen to the sounds, or you could smash it and collect all the pieces. Putting the pieces back together allows you to reconstruct the contents of the box. Likewise, Dr Neveling allows a fast-moving beam of particles to smash into a thin target, and then he collects all the reaction products using a detector in order to investigate the structure and behaviour of particles.

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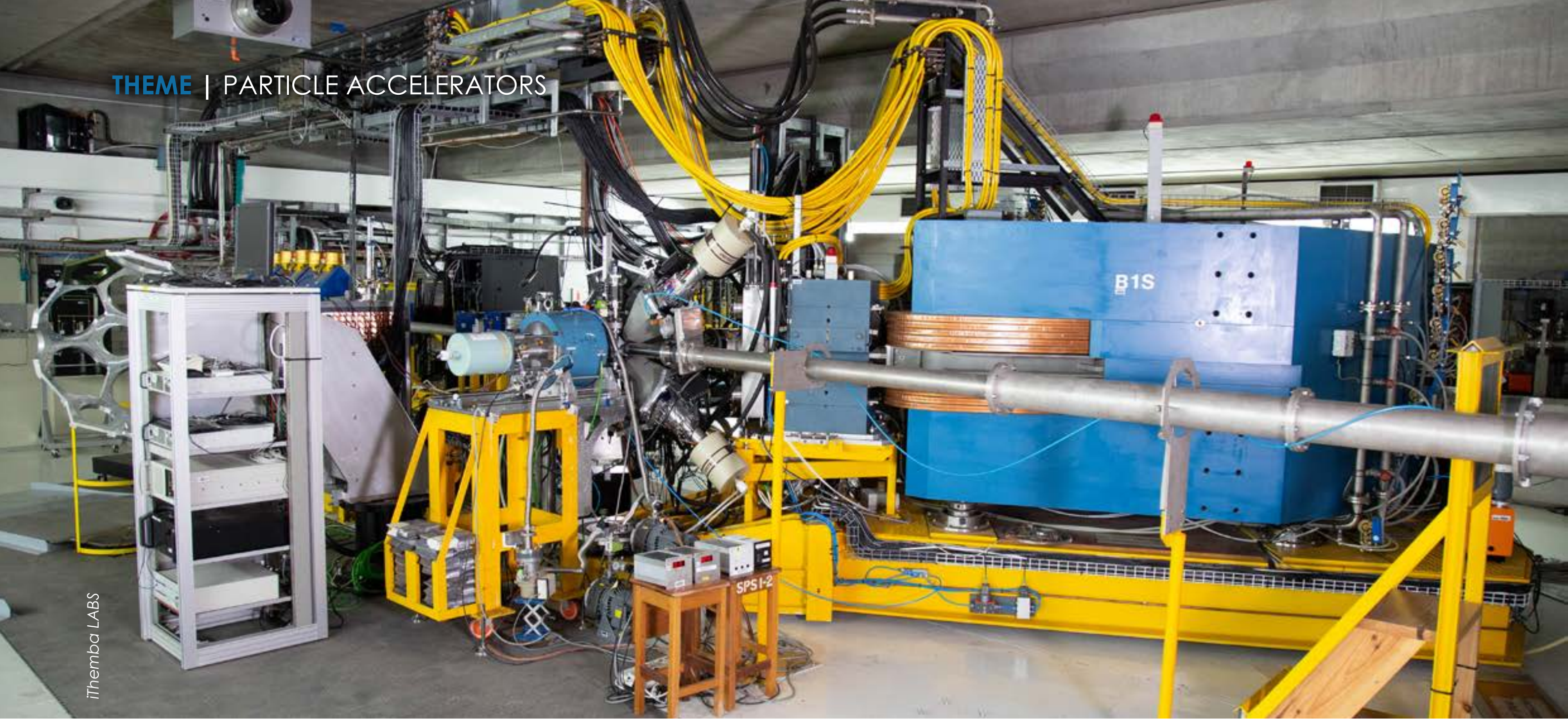
The Separated Sector Cyclotron (SSC) is the largest accelerator at iThemba LABS. The magnetic fields are largely contained within the yellow sectors of the accelerator.



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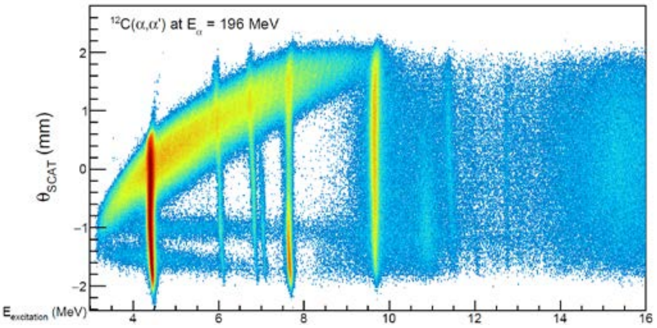
The k600 magnetic spectrometer is capable of measuring inelastically scattered particles and reactions at extreme forward angles, including 0°. This makes it one of only two such facilities in the world capable of measuring at 0°.

One of the biggest detector set-ups at iThemba LABS is the k600 magnetic spectrometer. This 100-tonne detector can generate a relatively strong magnetic dipole field of up to 1.64 Tesla, which is approximately 30 000 times stronger than the Earth's magnetic field at the surface. The field is strong enough to bend protons moving at 56% the speed of light through a radius of just 2.1 m.

Magnetic fields make it possible to manipulate fast-moving charged particles when the particle's mass, speed and charge are known. These three quantities can be rolled up into one concept, namely the particle's rigidity (R). The higher the rigidity, the more difficult it is to change the particle's direction – in other words the more rigid its trajectory is. For example, it is more difficult to change the direction of a faster/heavier particle than a slower/lighter particle. Similarly, a particle with more charge is affected more by a magnetic field than a particle with less charge.

Dr Neveling makes use of this concept to measure, with high accuracy, the kinetic energy of fast-moving reaction products following a nuclear reaction. With sub-millimetre precision, he detects where the particles exit the spectrometer and, in this way, determines their rigidity. The type of particle is identified by measuring the time it takes the particle to traverse the magnetic field (to better than 1 nanosecond accuracy), as well as the amount of energy deposited in the detector at the spectrometer's exit. All these bits and pieces allow him to reconstruct the interaction between the energetic projectile and the target.



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Typical experimental results obtained with the k600 spectrometer for the inelastic scattering of alpha-particles off ^{12}C. Each vertical line represents a specific excited state in a nucleus. The majority are from ^{12}C, with a few contamination states seen due to the presence of ^{16}O in the target. The strong diagonal line represents alpha scattering from hydrogen.

One such study concerns the structure of the Hoyle state. This is an excited state in carbon-12 (^{12}C) at 7.654 MeV, which plays a pivotal role in the creation of carbon in stars and – by extension – the existence of carbon in the universe. The nuclear structure of this famous state is not yet understood, nor is the character of states in ^{12}C around 10 MeV fully explored. A possible way of studying the Hoyle state in ^{12}C is through inelastic scattering of alpha-particles, which consist of two protons and two neutrons, making them identical to the nuclei of helium atoms. This entails allowing fast-moving alpha-particles to interact with a ^{12}C-target and detecting the alphas after the collision at a reduced energy. The reduction in energy is related to the energy absorbed by the nucleus, and allows the researcher to extract information about the structure of ^{12}C, and therefore the Hoyle state. The strong dipole magnetic field in the magnetic spectrometer results in particles with different energies exiting the magnetic field at different places. The highest-energy particles, which imparted the smallest amount of energy to the ^{12}C nucleus, will be bent less than the lower-energy ones which excited the ^{12}C more.

By detecting and studying such phenomena at the sub-atomic level, iThemba LABS is truly a place where all the science we are taught at school comes to life!

- For more detailed information, read the laboratory portrait published in *Nuclear Physics News*. https://tlabs.ac.za/wp-content/uploads/pdf/iTL_portrait.pdf

Dr Gillian Arendse is the head of communications and stakeholder relations at iThemba LABS, and a well-known motivational speaker. He completed his PhD in experimental nuclear physics at Stellenbosch University in 1996.

Large Hadron Collider

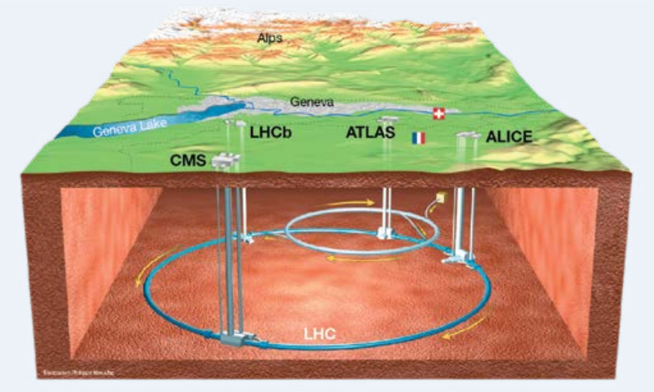
The world's most powerful particle accelerator is the Large Hadron Collider at CERN – the European Organisation for Nuclear Research. Referred to by scientists as the LHC, the accelerator is in a circular tunnel located 100 m underground at the French-Swiss border near Geneva, Switzerland. Its full name refers to:

- 'Large' because its circumference is about 27 km
- 'Hadron' because it accelerates quark-containing particles called hadrons, such as protons
- 'Collider' because the particles form two beams travelling in opposite directions, which are made to collide at four different points.

The beams travel at close to the speed of light, which means that a proton goes round the LHC circuit more than 11 000 times per second! The beams are in two separate beam pipes, or tubes, kept at ultrahigh vacuum with a pressure similar to that of the moon's atmosphere. Thousands of magnets of different varieties and sizes – many of them 15 m long – direct the beams around the accelerator.

There are seven experiments installed at the LHC. Construction work on the first four began between 1996 and 1998. These are located in huge underground caverns built around the four collision points of the LHC beams and are called A Large Ion Collider Experiment (ALICE), A Toroidal LHC ApparatuS (ATLAS), the Compact Muon Solenoid (CMS), and the Large Hadron Collider beauty (LHCb) experiment. The smaller Large Hadron Collider forward (LHCf) experiment, TOTal Elastic and diffractive cross section Measurement (TOTEM) experiment, and Monopole and Exotics Detector at the LHC (MoEDAL) were added later.

The experiments use detectors to analyse the particles produced by collisions in the accelerator. In July 2012, CERN announced the discovery in both the ATLAS and CMS experiments of the Higgs boson, a fundamental particle predicted to occur by Peter Higgs, François Englert and other theorists. Following this confirmation of its existence, Higgs and Englert were awarded the Nobel Prize for Physics in 2013.



CERN, CC-BY-4.0

Schematic view of the Large Hadron Collider (LHC), with the four largest detectors.

SA-CERN programme

The LHC experiments are run by collaborations of scientists from institutes all over the world, including South Africa. The SA-CERN programme is a national programme hosted by iThemba LABS and funded by the Department of Science and Innovation (DSI) and the National Research Foundation (NRF) to provide South African researchers, students, engineers and technicians with an opportunity to participate in the activities at CERN. This includes taking part in the ATLAS and ALICE experiments, as well as those at CERN's radioactive ion beam facility called ISOLDE, which stands for Isotope Separator On Line Device. In addition, South Africans contribute to theoretical physics related to the research at CERN.

ATLAS Collaboration, CERN

Humphry Tlou is the first South African to be awarded the ATLAS PhD Grant.

The SA-CERN programme makes a limited number of bursaries available for MSc and PhD studies in CERN-related research. South Africans can also apply for international funding, such as the ATLAS PhD Grant offered by the CERN & Society Foundation. In December 2020 it was announced that a physics PhD student at the University of the Witwatersrand, Humphry Tlou, was one of two recipients of the 2021 ATLAS PhD Grant, the other being a female PhD student from Portugal. Tlou is the first South African to have been awarded this grant, and he has also received financial support through the SA-CERN programme, having been involved in ATLAS activities since 2015 as a final-year undergraduate student and then travelling to CERN for the first time in 2017.

Currently the LHC is in a 'long shutdown', which started in December 2018, for maintenance and upgrades before the next 'run' period, due to start in early 2022. Tlou explained during the grant award ceremony, held online, that he is contributing to the upgrade, development and management of the data acquisition software for the ATLAS Tile Calorimeter, a sub-detector of ATLAS. This will allow the 'TileCal' group to operate the detector and collect data for physics analysis, including for his own PhD focusing on the search for a new boson, heavier than the Higgs boson.

Tlou's PhD supervisor is Prof. Bruce Mellado, Director of the Institute for Collider Particle Physics (IPP) in the Wits School of Physics, and a senior scientist at iThemba LABS. In May, Mellado was elected Chairperson of ATLAS TileCal's Institutional Board by representatives of 25 research institutes worldwide.

For more information about CERN facilities and science, refer to: https://home.cern/resources/brochure/knowledge-sharing/lhc-facts-and-figures