

Introducing the LHC in the classroom: an overview of education resources available

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Abstract

In the context of the recent re-start of CERN's Large Hadron Collider (LHC) and the challenge presented by unidentified falling objects (UFOs), we seek to facilitate the introduction of high energy physics in the classroom. Therefore, this paper provides an overview of the LHC and its operation, highlighting existing education resources, and linking principal components of the LHC to topics in physics curricula.

Introduction

Early in 2015, CERN's Large Hadron Collider (LHC) was awoken from its first long shutdown to be re-ramped for Run 2 at unprecedented beam energy and intensity. Intense scrutiny was required to verify the full and proper functioning of all systems. This included a special run of the machine to ensure a well-scrubbed LHC [1]. However, due to the increased beam currents, a critical but familiar issue reared its head during the run. Interactions between the beams and unidentified falling objects—so called UFOs—led to several premature protective beam dumps (see figure 1). These infamous UFOs are presumed to be micrometre-sized

dust particles and can cause fast, localised beam losses with a duration on the order of 10 turns of the beam. This is a known issue of the LHC which has been observed before. Indeed, between 2010 and 2011, about a dozen beam dumps occurred due to UFOs and more than 10000 candidate UFO events below the dump threshold were detected [2]. Thus, UFOs presented more of an annoyance than a danger to the LHC, by reducing the operational efficiency of the machine. However, as beam currents increase, so does the likelihood of UFO-induced magnet quenches at high energy, creating a possible hazard to the machine. Therefore, particular care is taken to keep an eye on the timing and frequency of UFO occurrences. As the number of UFOs during Run 1 decreased over time, it is hoped that this will be the same in Run 2.

The recent re-start of the LHC at higher collision energies and rates presents high school



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teachers with a unique opportunity: to use the LHC as a prime example of fundamental research, further integrating modern physics into their physics classes. We consider the re-start of the LHC, in combination with the intriguing phenomenon of UFOs, to be well-suited to engage students with high energy physics. Therefore, the aim of our paper is to give a broad overview of the LHC and its operation and to link each aspect of these to a range of existing education resources. In addition, we highlight specific connections to physics curricula to facilitate the integration of high energy physics in the classroom.

The operation of the LHC

The ultimate goal of the LHC is to collide beams of electrically charged particles at unprecedented energies and luminosities. Large detectors are installed around the collision points in order to explore the structure of matter, better understand the evolution of the Universe, and unambiguously discover new particles [4].

Particle beams

CERN's historic accelerator complex [5, 6] provides beams of either protons or, about one month per year, lead ions. Interconnected particle accelerators speed up these particles to energies of up to 7 TeV. Particles are taken from sources, marking the beginning of the complex. One of the sources is an ordinary bottle of hydrogen gas. Molecular hydrogen is fed from the bottle into a chamber, where its protons are separated from its electrons by an electron gun. These protons are guided by electric fields through vacuum chambers into the first accelerating machines. The last of these take care of the final beam structure, which is not a continuous stream of particles but consists of packages of protons, known as 'bunches' (see figure 2(a)). In the LHC, this leads to the ultimate fill with about 2800 bunches of ultra-relativistic protons for each of the counter-rotating beams at a bunch spacing of 25 ns. A bunch contains about a hundred billion protons while being a few centimetres long and having a horizontal spread between millimetres and a few micrometres. In order to provide the detector experiments with high-quality collisions for a sufficient period of time, an ultra-high vacuum,

on the order of 10^{-10} mbar, must be imposed on the chambers surrounding the beams.

Various papers have been published encouraging the use of the LHC as an education resource. Among these, relevant to the teaching of particle beams, are descriptions and calculations of the vacuum system [7] and the energy stored in individual LHC components [8]. In addition, a new set of state-of-the-art animations by CERN's MediaLab illustrates many aspects of the operation of the LHC, including the process of producing particle beams for the LHC [9]. When introducing particle beams in the classroom, these can all be combined to cover several topics. Ionisation, a phenomenon described by quantum physics, is the dominant production process of electrically charged particles in accelerators. Their properties and behaviour after being accelerated to ultra-relativistic energies are described by special relativity. The record-breaking numbers describing the LHC beams, such as the energy of 7 TeV applied to protons, allow the introduction of physics quantities in mechanics, including energy, velocity, momentum, and mass. The astonishing quality of the vacuum in the LHC beam pipes can be used to discuss thermal physics. Phenomena of electricity, such as electromagnetic induction, are used in the LHC in several instances, e.g. determination of the LHC beams' positions and intensities by beam position monitors [10]. Particle beams represent a source of ionising radiation and therefore possible hazard to humans. Their penetrating power, however, can also be used in medical applications, such as cancer treatment. Thus, particle beams invite one to speak about interdisciplinary topics, e.g. radiation protection [11] and medical applications [12]. When being smashed together as they are in the LHC, particles interact in numerous ways. Three of the four fundamental interactions in Nature—namely, the strong, weak, and electromagnetic interactions—and their laws can be studied, which gives an opportunity to introduce particle physics into the classroom.

Radiofrequency cavities

The beams of electrically charged relativistic particles described above are delivered to the LHC at an injection energy of 450 GeV [5]. Thus, to produce collisions at the desired energy of 14 TeV (7 TeV per colliding proton), the beams must be further accelerated. Moreover, due to synchrotron

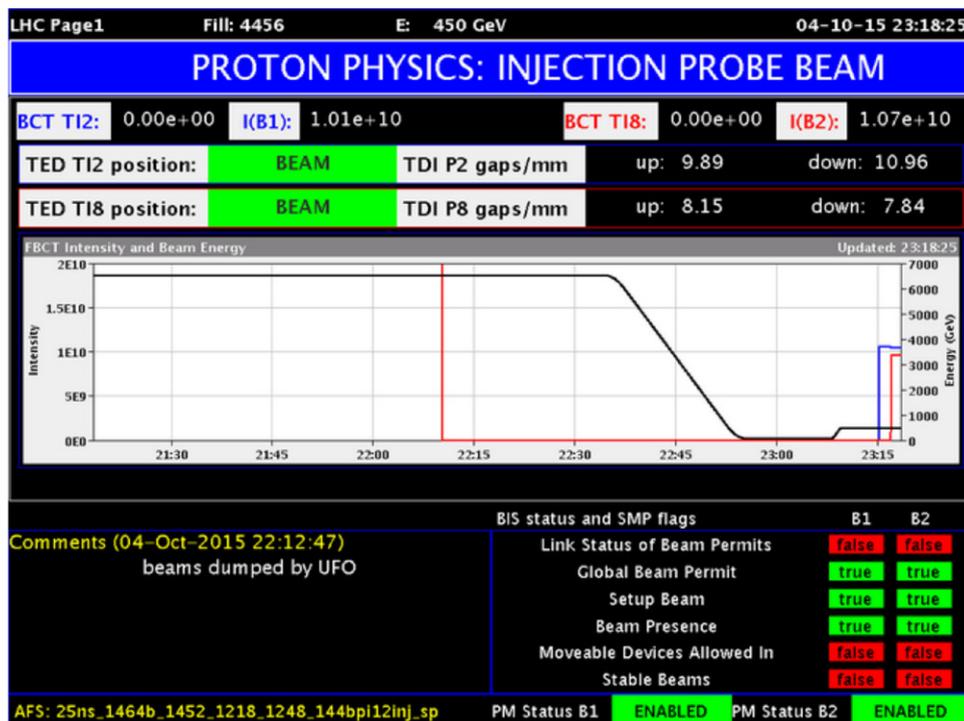


Figure 1. Screenshot of LHC Page1 after a beam dump by a UFO (image courtesy of CERN). This display of current activities of the LHC, as well as details about all the other particle accelerators at CERN, can be found online [3].

radiation, the particles constantly lose energy which must be fed back to them, even once they reach their final energy. This is achieved through the use of radiofrequency (RF) cavities, hollow copper structures coated with a $1.5 \mu\text{m}$ thick niobium layer on the inside. The outside of the cavities is cooled with liquid helium to an operating temperature of 4.5 K. At this low temperature, the niobium is superconducting, allowing a more cost-effective operation compared to normally conducting cavities [13]. The cavities are hosted alongside cryogenic and RF equipment in mechanical support structures called ‘cryomodules’ (see figure 2(b)). There are four cryomodules containing four cavities each, all grouped together at one of the straight sections of the LHC, with two cryomodules per beam. High-power RF generators, called klystrons, feed each cavity with an electromagnetic field via waveguides. This field oscillates at a period compatible with the duration of the particles’ passage around the LHC. As a result of the superposition of electromagnetic waves moving back and forth inside the cavities

at their resonant frequency of 400 MHz, standing electromagnetic waves are generated. Their associated electromagnetic fields produce longitudinal electric fields of about 5 MV m^{-1} along the beams’ directions. Provided ideal timing of the particles’ arrival at the cavities, these alternating electric fields can be used to transfer energy to the particle beams each time they pass through. With each lap around the LHC, every proton thus gains on average 485 keV in energy. The process of acceleration from injection to collision energies takes about 20 min, or about 1 million laps of the ring [6, 13].

Introducing the process of accelerating particles is supported by many education resources, for example a simple calculation on the sheer amount of protons circulating in the LHC [14], which is well-suited for high school students. Additionally, hands-on experiments allow for more practical engagement by enabling students to build models of particle accelerators in the classroom [15]. The operation and functioning of the RF cavities used for the LHC is illustrated in

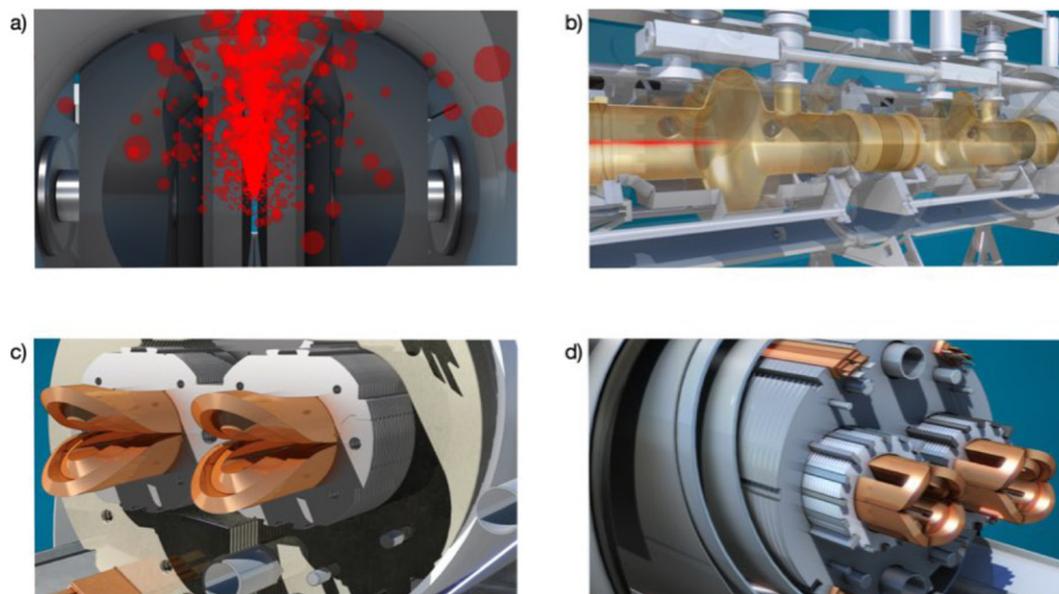


Figure 2. Graphical visualisations of (a) a particle beam; (b) two of the four radiofrequency cavities inside a cryomodule; and coils of superconducting NbTi cables in (c) dipole and (d) quadrupole magnets (images courtesy of CERN).

another CERN MediaLab animation [16]. High school teachers can use RF cavities to illustrate several topics of physics curricula. For example, principles of electricity, such as electrostatics, are fundamental to the functioning of RF cavities. Furthermore, discussions of the electromagnetic waves used to accelerate particles can underpin discussions of mechanics, specifically regarding oscillations and waves. Finally, superconductivity, being a macroscopic effect of quantum mechanics, can serve as an example of quantum physics aspects of particle physics.

Dipole magnets

Key to every circular particle accelerator are magnetic fields. To bend accelerated particle beams into closed paths, magnetic dipole fields are essential. These uniform fields have a pure bending effect on electrically charged particles by virtue of Lorentz force. The movement of an electrically charged particle in a magnetic dipole field thus depends on the particle's velocity and the properties of the magnetic field. In the case of the LHC, the state-of-the-art version of a synchrotron, the guiding magnetic field is produced by high electric current in superconducting coils, which are placed close to the beam pipes (see

figure 2(c)). A total of 1232 so-called 'dipoles' are installed in the LHC tunnel. Each dipole is 15 metres long and their coils are made of niobium-titanium (NbTi) cables, which must be operated at a fraction of their critical temperature (10 K) to ensure superconductivity. The required operating temperature of 1.9 K is reached by using superfluid helium [17]. Thus, superinsulation and thermal shields are key components of each dipole to maintain the challenging temperature gradient between the cold mass and the outside. In addition, shrinking vessels also play a big role during cool-down, as every dipole contracts with temperature, yielding a total shortening of approximately 80 metres of the LHC's circumference [6]. When cooled down and operational, the dipoles can produce a magnetic field of up to 8.3 T by suitable distribution of a nominal electric current of around 12 kA through the superconducting cables [4]. At the designed maximum collision energy of 14 TeV, this magnetic field is required to keep the proton bunches on their intended trajectory.

Every dipole produced needed to be tested thoroughly before being installed at the LHC tunnel. Therefore, all dipoles were transported to CERN's magnet testing facility hall, where each was individually attached to a test bench to

simulate operational conditions. Of main interest during the testing were the vacuum in the beam pipes and the insulation vacuum. Only once it was shown that the cryostat's insulation was sufficient could the magnet be cooled down. Once the dipole reached operation temperature, electric voltage was applied to the coils to scrutinise the magnetic field produced [18].

As for classroom application, we believe that by going through the described testing process and discussing the physics behind the dipoles, one can demonstrate the variety of physics phenomena coming into play. We identified three main curriculum topics standing out when discussing dipoles: starting with thermal physics to describe the cool-down process and operation, then making the link to electromagnetism when explaining how the magnetic field is produced through superconducting coils, and finally leading to mechanics for the discussion of the Lorentz force and the circular motion of the accelerated particle beams. Here, useful resources have already been published, mainly focusing on LHC's dipoles by providing calculations of their impedance [8], as well as of the Lorentz force and the magnetic energy required [19]. Once again, an animation is also available, showing the operation and functioning of the LHC's dipoles [20].

Quadrupole magnets

In addition to dipole magnets, which ensure the circular paths of the particle beams, many other superconducting electromagnets with a variety of configurations are used to keep the trajectories of the electrically charged particles close to the ideal orbit [21]. Among these are quadrupole magnets, which consist of four coils arranged around the beam pipes (see figure 2(d)). The strength of the resulting magnetic quadrupole field increases linearly with displacement from the centre. The resulting linearly increasing Lorentz force leads to a focusing effect on a beam of electrically charged particles like protons [6]. Because of the shape of the magnetic field, one quadrupole magnet will always focus in one direction, e.g. horizontally, and defocus in the other direction, e.g. vertically. To produce radially focused beams, a combination of focusing and defocusing quadrupole magnets is used.

In a circular collider like the LHC, focusing is not only needed to continuously compensate the repulsion between particles of the same electric charge due to the Coulomb force, but also to dramatically reduce the beams' diameters to a minimum size of $16.7 \mu\text{m}$ as the beams approach each interaction point [13]. Small beam diameters are crucial for high collision rates inside the LHC detectors. To achieve the necessary magnetic field gradients of up to 205 T m^{-1} inside the quadrupole magnets, the same superconducting NbTi cables are used as in the LHC dipole magnets [21].

Especially when placed close to an interaction point where particle interactions take place about 800 million times per second, magnets must be designed taking into account the flux of emerging secondary particles. Up to 30W of thermal load is produced in a quadrupole magnet when energy of secondary particles is deposited inside the magnet material. To prevent the magnets from quenching and thereby losing their superconducting properties, heat exchanger pipes carry superfluid helium at 1.9K, which absorbs heat through vaporisation [22]. In addition, radiation damage due to an accumulated dose of approximately 23 MGy during the first ten years of operation had to be considered in the design process [23].

Discussing quadrupole magnets allows a variety of connections to the physics curriculum. To guide and focus beams of electrically charged particles, scientists have adapted many concepts from optics, e.g. quadrupole magnets are often compared to lenses. In the classroom, focusing and defocusing effects of quadrupole magnets can easily be demonstrated by using four identical coils and a cathode ray tube [24]. A simple visualisation of complex multi-pole magnetic fields can be realised by using cheap magnetic toys, such as GEOMAG™ [25]. Thermal physics is key in describing enthalpy of vaporisation and the importance of cryogenic plants at the LHC, whereas interactions of secondary particles with the magnets themselves are described by applying fundamental principles of particle physics. To illustrate the operation and functioning of the LHC's quadrupoles, teachers can make use of yet another animation, made available online by CERN's MediaLab [26].

Conclusion

Over the last few years, CERN's LHC has become widely known as the most powerful particle accelerator of our generation and has sparked significant interest in high energy physics. To help high school teachers respond to this demand, we have given an overview of the LHC and its operation while linking it to resources which could be of use in the classroom. Furthermore, we have introduced a current challenge facing operators of the LHC, UFOs, which may stimulate high school students' interest in high energy physics.

Furthermore, we want to stress that several educational outreach programmes have been established, prompting a multitude of approaches towards the introduction of the physics behind the LHC into the classroom. For instance, in coordination with CERN's LHC outreach group, every major LHC detector collaboration runs their own education and outreach programme, facilitating the creation and distribution of helpful material and useful resources on particle detection for high school teachers [27–30]. Indeed, many resources on the LHC and its detectors are available online in various degrees of quality, scope, and elaboration. The international particle physics outreach group (IPPOG) maintains a database of resources [31] containing an extraordinary and ever-growing range of tools and materials, such as teaching and exhibition material, educational games, podcasts, and many more. A prominent example is IPPOG's programme of International Masterclasses [32], enabling high school students to perform hands-on measurements on real data from the four main LHC detectors. This goes hand-in-hand with CERN's open data portal [33], which acts as an access point to research data produced at CERN.

As the LHC enters Run 2, this is an exciting time for high energy physics and a prime opportunity for high school teachers to introduce this modern topic in the classroom. We hope, therefore, that the resources referenced above and our overview of the LHC and the challenges involved in its operation will support high school teachers in this endeavour.

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Julia Woithe is a high school teacher for physics and mathematics. She is currently working on her PhD project in physics education research at CERN, Geneva, Switzerland in cooperation with the University of Kaiserslautern and the University of Geneva. Her project is S'Cool LAB, the new hands-on particle physics learning laboratory at CERN. She is interested in students' conceptions and low-cost experiments in modern physics.



Alexander Brown has a background in hands-on science communication in Bristol and Bath, UK. He is currently carrying out a PhD at the Institut Universitaire pour la Formation des Enseignants at the University of Geneva, Switzerland. His research looks into the use of online e-learning tools to prepare high school students for visits to CERN's S'Cool LAB.



Konrad Jende worked as a high school teacher for physics and mathematics in Dresden, Germany. He joined the CERN doctoral student programme to develop an educational activity for IPPOG's International Masterclasses allowing students to analyse real data from the ATLAS experiment at the LHC. He is now coordinating the national and international teacher training programmes at CERN, Geneva, Switzerland.