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Taking energy to the physics classroom from the Large Hadron Collider at CERN

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Abstract
In 2008, the greatest experiment in history began. When in full operation, the Large Hadron Collider (LHC) at CERN will generate the greatest amount of information that has ever been produced in an experiment before. It will also reveal some of the most fundamental secrets of nature.

Despite the enormous amount of information available on this topic, it is not easy for non-specialists to know where the data comes from. The aim of this article is to introduce at a secondary school level a few simple physical calculations about power phenomena that will be present in the LHC: stored beam energy, power and LHC dipole, energy stored in the compact muon solenoid (CMS), energy stored in the ATLAS solenoid and toroid, delivered energy for radiofrequency (RF) cavities, and energy dissipated in dump blocks. In addition, we will be talking about one of the most important scientific institutions in the world and introducing the greatest experiment in history.

The calculations that you will find in this article are adapted from physics at secondary school level, and in most cases they are just very simple approaches to the correct results.

The large hadron collider (LHC) at CERN

The European Organization for Nuclear Research (originally the Conseil Européen pour la Recherche Nucléaire), commonly known as CERN, is the world's largest particle physics laboratory, situated in Geneva on the border between France and Switzerland. Its main function is to provide the particle accelerators and other infrastructure needed for high-energy physics research. Numerous experiments have been constructed at CERN by international collaborations to make use of them. CERN's biggest particle accelerator is now the Large Hadron Collider (LHC). It will smash protons together in head-on collisions at energy levels higher than ever achieved before. The collider has been built inside an already existing circular tunnel that is almost 27 km (26659 m) in circumference and about 100 m underground.

The LHC will provide proton–proton collisions with a centre-of-mass energy of 14 TeV and a very high number of collisions per second and per cm^2 (luminosity). In order to achieve this, the collider must operate with more than 2808 bunches per beam and a very high intensity (1.15×10^{11} protons per bunch); this requires more

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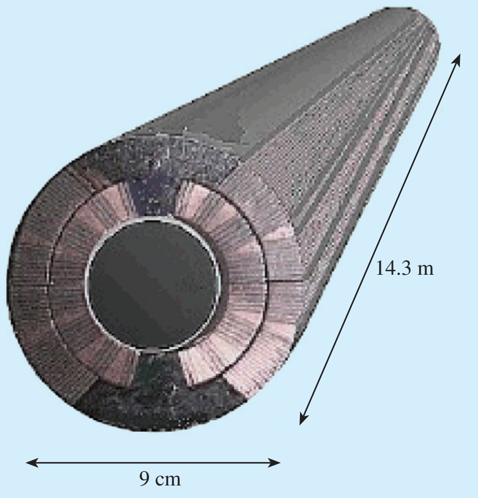

Figure 1. The LHC dipole considered as a cylindrical coil.

than 8000 superconducting magnets of different types. The most challenging part of the LHC is the 1232 superconducting dipoles, which must operate reliably at the nominal magnetic field of 8.33 T.

Stored beam energy

How much energy are we talking about?

$$7 \text{ TeV} = 7 \times 10^{12} \text{ eV}$$

$$7 \times 10^{12} \times 1.6 \times 10^{-19} = 1.12 \times 10^{-6} \text{ J}.$$

This does not look like a lot of energy. Let us calculate the kinetic energy of a 60 mg insect flying at 20 cm s^{-1}:

$$E_\text{k} = 1/2mv^2$$

$$E_\text{k} = 1/2 \times 6 \times 10^{-5} \times 0.2^2 \sim 7 \text{ TeV}.$$

That is, in the LHC each proton will reach an energy similar to that of an annoying . . . mosquito! But we have to keep in mind that this mosquito has 36 thousand trillion nucleons, whereas the 7 TeV in the LHC will be concentrated in one sole proton.

Maybe this comparison is not very convincing, so let us look at it from another point of view. Let us calculate the energy present in each bunch:

$$7 \text{ TeV/proton} \times 1.15 \times 10^{11} \text{ protons/bunch}.$$

So, there is 1.29×10^5 J/bunch.

A powerful motorbike weighing 150 kg travelling at 150 km h^{-1} has kinetic energy

$$E_\text{k} = 1/2 \times 150 \times 41.7^2 \sim 1.29 \times 10^5 \text{ J}.$$

So, if a bunch of protons collides with you the impact is similar to that produced by a powerful motorbike travelling at 150 km h^{-1}. If you are lucky to avoid that ‘0.2 pg motorbike’, do not worry; there are 2807 following it. And if you decide to change lanes, the equivalent is coming in the opposite direction.

Another calculation which can show the enormous amount of energy reached is

$$1.29 \times 10^5 \text{ J/bunch} \times 2808 \text{ bunches}$$

$$\sim 360 \text{ MJ}.$$

This represents the stored beam energy, and is equivalent to the energy produced in the explosion of 77.4 kg of TNT.

Let us calculate the amount of gold we might melt from 25 °C by using 360 MJ of energy.

Latent heat of fusion (H_F): 64 kJ kg^{-1}

Specific heat capacity (c_e): 130 J kg^{-1} K^{-1}

Melting point = 1340 K.

So, 360 MJ (Q) is enough to melt

$$Q = mc_e\Delta t + mH_\text{F}$$

$$360 \times 10^6 = m \times 130 \times (1340 - 298) + m \times 64 \times 10^3$$

$$m \approx 1800 \text{ kg} = 1.8 \text{ tonnes of gold}.$$

Obviously, 360 MJ per beam is an amount of energy that cannot be supplied instantly. In fact, the process lasts 25 min, through a chain of different accelerators.

Energy and the LHC dipole

1232 magnetic dipoles (14.3 m long and weighing around 35 tonnes) placed along the beam path will produce the force which will permanently bend the protons’ trajectory. The circulating electrical current is 11 800 A.

First, we have to calculate the dipole inductance. Let us consider the LHC dipole to be like a cylindrical coil (14.3 m long and 9 cm wide on average) with 80 turns and a perpendicular

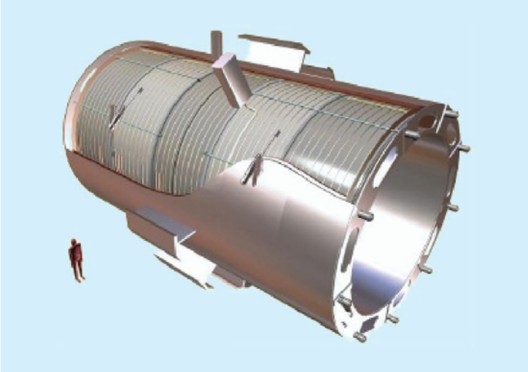

Figure 2. The CMS solenoid. Courtesy of CERN.

magnetic field 8.33 T (see figure 1). The magnetic flux throughout the surface is

$$\varphi = N \times B \times S, \qquad \varphi = 80 \times 8.33 \times (14.3 \times 0.09)$$

$$\varphi \approx 1000 \text{ Wb}.$$

With

$$\varphi = L \times I, \qquad L = 1000/11800,$$

so,

$$L \approx 0.1 \text{ H}.$$

Thus, the stored energy is

$$E_d = 1/2L \times I^2, \qquad \mathbf{E}_d \approx 7 \text{ MJ}.$$

Considering 1232 dipoles, $\mathbf{E}_T \approx 9$ GJ. This is enough to completely melt 45 tonnes of gold from 25 °C.

If we consider the dipole length, the energy density per unit length of the LHC magnets is

$$7 \text{ MJ}/14.3 \text{ m} \approx 500 \text{ kJ m}^{-1}.$$

The compact muon solenoid (CMS) and energy stored

The compact muon solenoid (CMS) is one of two general-purpose LHC experiments (ATLAS is the other) designed to explore the physics of the terascale, the energy region where physicists believe they will find answers to the central questions at the heart of 21st-century particle physics.

Its magnet consists mainly of three parts: a superconducting coil, a vacuum tank, and the magnet yoke. The solenoid produces an axial field whereas the yoke is responsible for the return of the magnetic flux.

The solenoid consists of five distinct modules (2.5 m length). Each module consists of an aluminium cylinder with four internal layers of winding, each with 109 turns (see figure 2). So,

$$N = 5 \times 4 \times 109 = 2180 \text{ turns}.$$

The total length of the solenoid is

$$d = 5 \times 2.5 \text{ m} = 12.5 \text{ m}.$$

The current intensity will be $I = 19500$ A. So,

$$B = \mu_0 N I/d, \qquad B \approx 4 \text{ T}.$$

Let us now calculate the CMS inductance. The solenoid has 2180 turns, the magnetic field is 4 T, and the surface is

$$S = \pi \times 3^2 = 28.3 \text{ m}^2.$$

So, the magnetic flux throughout the surface is

$$\varphi = N \times B \times S, \qquad \varphi = 2180 \times 4 \times 28.3$$

$$\varphi \approx 230 \text{ kWb}.$$

With

$$\varphi = L \times I, \qquad L = 230\,000/19\,500,$$

$$L \approx 12 \text{ H}.$$

The total stored energy is

$$E = 1/2L \times I^2, \qquad E \approx 2.3 \text{ GJ},$$

equivalent to the energy produced in the explosion of half a tonne of TNT.

The ATLAS solenoid and energy stored

The ATLAS detector (A Toroidal LHC ApparatuS) is the world's largest general-purpose particle detector, measuring 46 m long, 25 m high and 25 m wide; its mass is 7000 tonnes and it consists of 100 million sensors that measure particles produced in proton–proton collisions in the LHC.

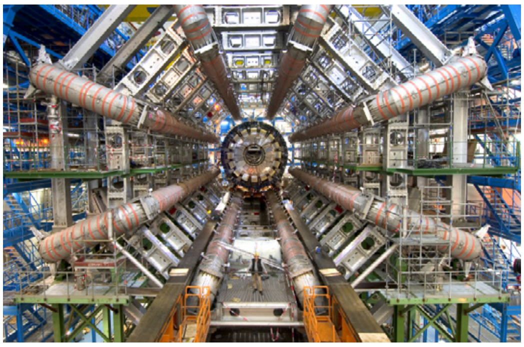

Figure 3. ATLAS toroid. Courtesy of CERN.

The ATLAS detector features a hybrid system of four superconducting magnets: a central solenoid surrounded by two end-cap toroids and a barrel toroid. The magnet system dimensions are 20 m in diameter and 26 m in length. With its 2 GJ stored energy in air, it is actually the largest superconducting magnet in the world.

The central solenoid, which is 5.5 tonnes in mass, 2.5 m in diameter and 5.3 m in length, provides an axial magnetic field of 2 T at the centre of the ATLAS tracking volume. It contains 7 km of superconducting wire cooled by liquid helium and an electric current of 8000 A. With 7 km of superconducting wire, the number of turns is

$$7000/(\pi \times 2.5) = 1142 \text{ turns.}$$

Since $B = \mu_0 \times N \times I/d$

$$B = (4\pi \times 10^{-7} \times 1142 \times 8000)/5.3$$

$$B \approx 2\,\mathrm{T}.$$

So, the magnetic flux throughout the surface is

$$\varphi = N \times B \times S, \qquad \varphi = 1142 \times 2 \times (\pi \times 1.25^2)$$

$$\varphi \approx 11\,200\,\mathrm{Wb}.$$

With

$$\varphi = L \times I, \qquad L = 11\,200/8000,$$

$$L \approx 1.4\,\mathrm{H}.$$

The stored energy is

$$E = 1/2L \times I^2, \qquad E \approx 44.8\,\mathrm{MJ}.$$

The energy stored in the ATLAS barrel toroid

The ATLAS detector also requires a large superconducting barrel toroid (BT) with overall dimensions of 25 m length and 22 m diameter. The barrel toroid provides the magnetic field for the muon detector. The toroid is assembled from eight flat race track coils of dimensions 25 m × 5 m (see figure 3). They were successively inserted in the underground cavern and assembled as a full toroid by using 16 supporting rings of struts that link the eight coils to form a rigid and stable structure.

The total mass of the toroid is 850 tonnes. The toroid system contains over 100 km of superconducting wire, and has a current design of 20 500 A.

Every flat race track coil is (25 + 25 + 5 + 5) = 60 m length. Since there is 100 km superconducting wire in the toroid we can consider that the number of equivalent turns is $100\,000/60 \approx 1670$. Since $B = \mu_0 \times N \times I/d$

$$B = (4\pi \times 10^{-7} \times 1670 \times 20\,500)/2\pi \times 8.5$$

$$B \approx 1\,\mathrm{T}.$$

So, the magnetic flux throughout the surface is

$$\varphi = N \times B \times S, \qquad \varphi = 1670 \times 1 \times (25 \times 5)$$

$$\varphi \approx 208\,750\,\mathrm{Wb}.$$

With

$$\varphi = L \times I, \qquad L = 208\,750/20\,500,$$

$$L \approx 10.2\,\mathrm{H}.$$

The stored energy is

$$E = 1/2L \times I^2, \qquad E \approx 2\,\mathrm{GJ}.$$

Let us compare this value with the take-off energy of the Airbus 380.

Maximum take-off mass: 560 tonnes.

Take-off speed: $\sim 300\,\mathrm{km\,h^{-1}}$.

So,

$$E = 1/2mv^2, \qquad E \sim 1/2 \times 560\,000 \times 83^2,$$

$$E \approx 1.9\,\mathrm{GJ}.$$

This is really very impressive.

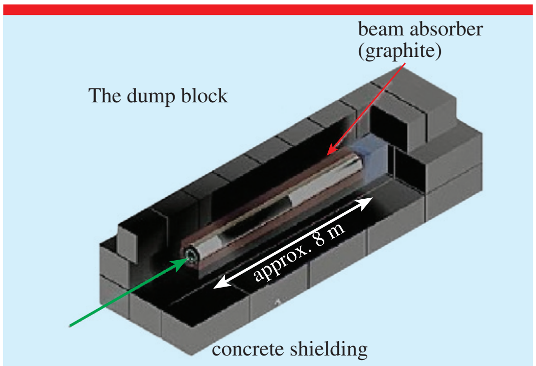

Figure 4. The LHC dumping system. Courtesy of CERN.

Radiofrequency (RF) cavities—energy delivered

The main role of the LHC cavities is to keep the 2808 proton bunches tightly bunched to ensure high luminosity at the collision points and hence maximize the number of collisions. They also deliver radiofrequency (RF) power to the beam during acceleration to the top energy.

The LHC use eight cavities per beam, each delivering 2 MV (an accelerating field of 5 MV m^{-1}) at 400 MHz. The cavities operate at 4.5 K—the LHC magnets will use superfluid helium at 1.8 K.

Let us calculate the energy delivered per second when the cavities are working at nominal power. Since each bunch travels at almost the speed of light, each one will go around

$$300\,000/26.659 = 11\,253 \text{ lap s}^{-1}.$$

In addition, we must take into account:
number of bunches per beam: 2808
protons per bunch: 1.15×10^{11}
proton electric charge: 1.602×10^{-19} C.
For each lap,

$$E = 8 \times 2 \times 10^6 \times 2808 \times 1.15 \times 10^{11} \times 1.602 \times 10^{-19}$$

$$E = 830 \text{ J/lap}.$$

Converting this to energy per second,

$$E = 830 \text{ J/lap} \times 11\,253 \text{ lap s}^{-1}$$

$$E = 9 \text{ MJ s}^{-1}.$$

Then, the power of the RF cavities is

$$P = 9 \text{ MW}.$$

The Super Proton Synchrotron (SPS) is the second largest machine in CERN's accelerator complex. Measuring nearly 7 km in circumference, it takes particles from the PS and accelerates them to provide beams for the LHC, the COMPASS experiment and the CNGS project.

Since protons are injected in the LHC (from the SPS accelerator) with 0.45 TeV, we can consider that the 7 TeV needed is provided by the RF cavities.

We have already calculated the stored beam energy, 360 MJ. So, after filling the LHC, the necessary time to take the beam to the top energy is

$$360/9 = 40 \text{ s}.$$

Dumping energy

The LHC beam dumping system is designed to make a fast extraction of the circulating beams from each ring of the collider with minimal losses. The particles are then transported to external dump blocks, which are located in caverns at the end of a 700 m long vacuum line. The two dump blocks are the only elements in the LHC that can withstand the impact of the full beam. The 8 m length blocks are made of graphite to spread the hadronic showers out over a large volume.

When it is time to get rid of the beams (also in case of emergency), the beams are 'kicked' out of the ring by a system of kicker magnets and sent into a dump block. A quenched dipole will require a beam dump in a single turn—(360 MJ per beam) dissipated in 89 ms! Each block is a cylinder of graphite composite 8 m long and 1 m in diameter, which is encased in concrete (see figure 4). As the block absorbs the beam energy, it becomes very hot but does not melt. This size allows the hadronic showers to spread out over a large volume.

At the moment of dumping, the stored beam energy is delivered to the block. So, the energy density inside the block is

$$\rho = 360/(8 \times \pi \times 0.5^2), \qquad \rho = 57.3 \text{ MJ m}^{-3}.$$

The total dissipated power is

$$P = 360/0.089, \qquad P = 4 \text{ GW}.$$

Powering the LHC and CERN

When the LHC is running the total average power for the whole CERN site will peak at about 180 MW, of which

- LHC cryogenics need 27.5 MW
- LHC experiments need 22 MW.

If we include the base load for the whole site, the LHC contribution totals around 120 MW.

CERN's predicted total for the year 2009 with LHC fully operational is around 1000 GW h (1 TW h), of which around 700 GW h might be attributed to the LHC (machine, experiments and base load).

The canton of Geneva uses 41 000 TJ (heating, transport, electricity) i.e. around 11.4 TW h, so CERN comes in at less that 10% of the total energy consumption of the canton.

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Further Reading

Taking a closer look at LHC www.lhc-closer.es/index.html
High School Teachers at CERN teachers.web.cern.ch/teachers/
CERN www.cern.ch
LHClhc.web.cern.ch/lhc/
Detector CMS cmsinfo.cern.ch/outreach/
Detector ATLAS atlas.ch
Detector ALICE aliceinfo.cern.ch/Public/
Detector LHCb lhcb-public.web.cern.ch/lhcb-public
TOTEM totem.web.cern.ch/Totem/
LHCf public.web.cern.ch/Public/en/LHC/LHCf-en.html

Xabier Cid Vidal graduated in physics in 2007. He is currently doing his PhD on experimental particle physics, taking part in the LHCb collaboration at CERN with the University of Santiago's group.

Ramón Cid graduated in physics and chemistry, and has taught physics at secondary school since 1980. He participated in the HST programme at CERN in 2003. He has coordinated various European teaching projects and several annual ENCIGA (Association of Science Teachers of Galicia) science teachers' congresses.