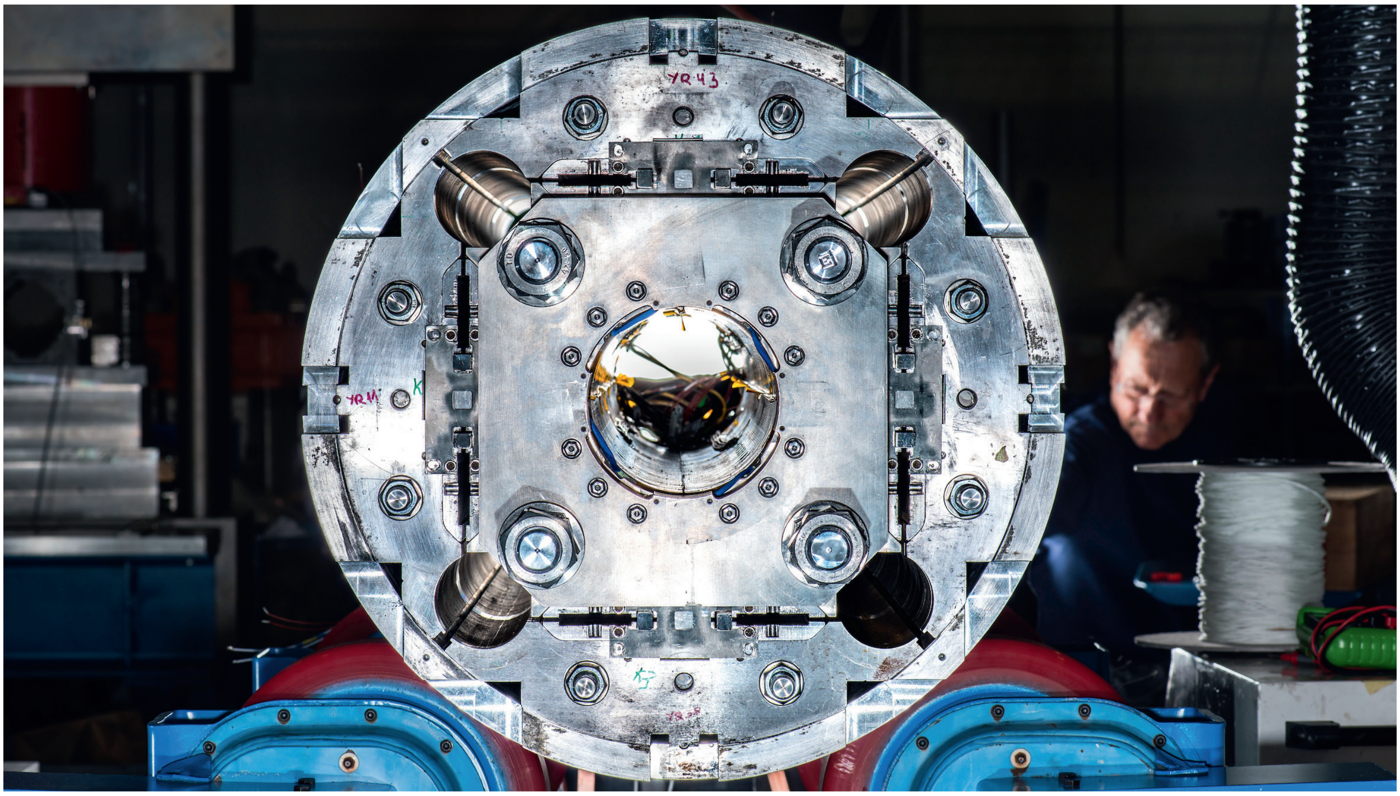
The High-Luminosity LHC:
a new horizon for science and technology

The High-Luminosity LHC (HL-LHC) is a major upgrade of the Large Hadron Collider (LHC). The LHC collides tiny particles of matter (protons) at an energy of 13 TeV in order to study the fundamental components of matter and the forces that bind them together. The High-Luminosity LHC will make it possible to study these in more detail by increasing the number of collisions by a factor of between five and ten.



Prototype of a quadrupole magnet for the High-Luminosity LHC. (Image: Robert Hradil, Monika Majer/ProStudio22.ch)

WHAT IS LUMINOSITY?
Luminosity, which is the measure of the number of potential collisions per surface unit over a given period of time, is an essential indicator of an accelerator's performance. Integrated luminosity is measured in inverse femtobarns (fb^{-1}); one inverse femtobarn equates to 100 million million collisions.

By the end of its first few years of operation at 13 TeV (at the end of 2018), the LHC should have produced 150 inverse femtobarns of data. The HL-LHC will produce more than 250 inverse femtobarns of data per year and will be capable of collecting up to 4000 inverse femtobarns.

WHY HIGH LUMINOSITY?
The phenomena that physicists are looking for have a very low probability of occurring and this is why a very large amount of data is needed to detect them. Increasing luminosity produces more data, allowing physicists to study known mechanisms in greater detail and observe rare new phenomena that might reveal themselves. For example, the High-Luminosity LHC will produce at least 15 million Higgs bosons per year, compared to around three million from the LHC in 2017.

HOW WILL THE HIGH-LUMINOSITY LHC WORK?
Increasing the luminosity means increasing the number of collisions: at least 140 collisions will be produced each time the particle bunches meet at the heart of the ATLAS and CMS detectors, compared to around 40 at present. To achieve this, the beam will need to be more intense and more focused than at present in the LHC. New equipment will need to be installed over about 1.2 of the LHC's 27 kilometres.

- **More powerful focusing magnets and new optics**
  New, more powerful superconducting quadrupole magnets will be installed on either side of the ATLAS and CMS experiments to focus the particle bunches before they meet. These magnets will be made of a superconducting compound, niobium-tin, used for the first time in an accelerator, which will make it possible to achieve higher magnetic fields than the niobium-titanium alloy used for the current LHC magnets (12 teslas as opposed to 8). Twenty-four new quadrupole magnets are currently in production. The use of niobium-tin magnets is an opportunity to test this technology for future accelerators.

  New beam optics (the way the beams are tilted and focused) will notably make it possible to maintain a constant collision rate throughout the lifespan of the beam.

- **"Crab cavities" for tilting the beams**
  This innovative superconducting equipment will give the particle bunches a transverse momentum before they meet, enlarging the

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overlap area of the two bunches and thus increasing the probability of collisions. A total of sixteen crab cavities will be installed on either side of each of the ATLAS and CMS experiments.

- **Reinforced machine protection**
As the beams will contain more particles, machine protection will need to be reinforced. Around one hundred new, more effective collimators will be installed, replacing or supplementing the existing ones. These devices absorb particles that stray from the beam trajectory and might otherwise damage the machine.

- **More compact and powerful bending magnets**
Two of the current bending magnets will be replaced with two pairs of shorter bending magnets and two collimators. Made of the superconducting niobium-tin compound, these new dipole magnets will generate a magnetic field of 11 teslas, compared with the 8.3 teslas of today's dipole magnets, and will thus bend the trajectory of the protons over a shorter distance.

- **Innovative superconducting links**
Innovative superconducting power lines will connect the power converters to the accelerator. These cables, which are around one hundred metres long, are made of a superconducting material, magnesium diboride, that works at a higher temperature than that of the magnets. They will be able to carry currents of record intensities, up to 100 000 amps!

- **An upgraded accelerator chain**
The HL-LHC's performance will also rely upon the injector chain, i.e. the four machines that pre-accelerate the beams before sending them into the 27-kilometre ring. This accelerator chain is being upgraded. A new linear accelerator, Linac4, the first link in the chain, is in the testing phase before replacing today's Linac2. Upgrades are also planned for the three other links in the accelerator chain: the PS Booster, the PS and the SPS.

WHAT IS THE WORK SCHEDULE?

In order to install the new equipment and move certain components around, new underground structures and surface buildings are required.

The civil engineering work began in April 2018 at LHC Point 1 (in Meyrin, Switzerland), where the ATLAS experiment is located, and at LHC Point 5 (in Cessy, France), the site of the CMS experiment. A shaft of around 80 metres will be dug on each site, as well as an underground cavern and a 300-metre-long service tunnel. This service tunnel will be linked to the LHC tunnel by four connecting tunnels. Five surface buildings will be built on each site.

In the meantime, the new equipment is being manufactured in Europe, Japan and the United States. Canada and China have also expressed an interest in supporting the project and contributing to the production of the state-of-the-art equipment. The experiments are also preparing for major upgrades of their detectors to deal with the deluge of data promised by the HL-LHC.

Installation of the first components (the 11-tesla bending magnets and their collimators, the beam instrumentation, some other collimators and the shielding) will begin during the second long shutdown of the LHC, in 2019 and 2020. But most of the equipment and the major experiment upgrades will be installed during Long Shutdown 3, between 2024 and 2026.

HOW MUCH WILL THE HIGH-LUMINOSITY LHC COST?

The materials budget for the accelerator is set at 950 million Swiss francs between 2015 and 2026, assuming a constant CERN budget.

WHO IS INVOLVED IN THE PROJECT?

CERN and its Member and Associate Member States are supported by an international collaboration of 29 institutions in 13 countries, including the United States and Japan.

HOW WILL SOCIETY BENEFIT FROM THE HL-LHC?

The HL-LHC will further our fundamental knowledge, which is CERN's primary mission. To develop the new machine, CERN is pushing several technologies to their limits, such as electrical engineering, notably in terms of superconductors, vacuum technologies, computing, electronics and even industrial processes. In the long term, these innovations will benefit our daily lives.

For example, superconducting magnets find applications in the fields of medical imaging and cancer treatment with particle beams (hadron therapy). There are also many prospects in the field of electrical engineering: European industry is studying the possibility of using magnesium diboride cables to transport high electrical power over great distances in a way that is sustainable for the environment.

The HL-LHC project is also contributing to the training of new scientists – physicists, engineers and technicians. Currently, around 200 students, doctoral students, post-doctoral researchers and fellows of 23 different nationalities are participating in the project.

HL-LHC Plan