Cern Report

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1 CERN

1.1 What is CERN

CERN, Conseil Européen pour la Recherche Nucléaire (the European Organization for Nuclear Research) is an international research institution based in Geneva, Switzerland. It is is one of the largest research institutions focused on scientific research, specifically particle physics, with its core motivation being to uncover what the universe if made of and how it works [1].
CERN was founded in 1954 following discussions among a small number of European and North American scientists in the 1040's who expressed the need for the establishment of a world-class physics research facility in Europe for the dual purpose of conducting research and facilitating international collaboration following World War II. The CERN convention, which was signed in June of 1953 by 12 member states, puts emphasis on the fact that the research conducted at CERN has to be purely scientific and shall not be used in any way on military applications along with the fact that all results must be published or otherwise made public. Since 1953, 11 other member states have joined. These member states are represented in the Council that is responsible for all decisions about the Organization and its activities, and in return they contribute to the capital and operating costs of CERN.
Besides these member states, there are also many countries and organisations involved with CERN through either co-oporation agreements, scientific contracts or collaborations. [2]

1.2 What is the purpose of the research at CERN?

There are several purposes of the research being conducted at CERN ranging from research projects to further our understanding of the universe as well as facilitating international collaboration.
The primary goal of CERN is to conduct research into understanding the basic elements of matter—fundamental particles—and how they interact with each other by facilitating particle accelerators. This includes research on particles such as quarks, bosons, leptons, etc [3].
CERN also aims to confirm or contradict the Standard Model of particle physics,

which describes the behaviours of all known fundamental particles and forces, taking into consideration limitations and unexplained phenomena like dark matter and dark energy. Some of the questions in this field that CERN is conducting research on is *Why is gravity so weak compared to other forces?* as well as *Why is the universe made only of matter, with hardly any antimatter?*[4]
In 2012, CERN discovered the Higgs boson using the Large Hadron Collider (LHC), which validated the concept of the Higgs field—a field of energy that exists throughout the universe and gives other particles their mass. Now there are still many unanswered questions regarding the Higg's Boson that still needs to be answered such as *Is there only one Higgs boson, and does it behave exactly as expected?* [4]
A huge amount of CERN's experiments involve accelerating particles to high energies and smashing them together using particle accelerators. These collisions recreate conditions similar to those just after the Big Bang, which can be used to study how the early universe evolved into its current form.
Besides particle experiments, CERN also made great advancements within the technological field. As an example of this, the World Wide Web was invented at CERN to help scientists collaborate on research. Furthermore, CERN also contributes to advancements in medical imaging, materials science, and computing.
Finally, CERN also serves as a symbol of international scientific cooperation, hosting scientists from over 100 different countries who work together on its experiments. This initiative was made in the aftermath of World War 2 to enfore international coorporation within Europe [1].

2 Magnets

2.1 Why do we need magnets

A magnet is an object that can produce a magnetic field and it has the capability of attracting opposite poles and repelling similar poles.
Magnets have several use cases, both in everyday life, in the medical field and for scientific research purposes. Magnets can for example be used in Magnetic Resonance Imaging (MRI) which is a medical imaging procedure that makes use of a magnetic field and radio waves to produce three dimensional detailed anatomical images. This procedure can be used to diagnose medical conditions such as tumours or brain disorders. Another use case for magnets in the medical field is using permanent magnets to inject a magnetically-sensitive fluid into the area of the body where the cancer exists and generate heat onto the cancer cells using a powerful magnet. This procedure will consequently kill the cancer cells without causing any harm to healthy organs [5].
Magnets can also be seen in may household objects. They, for example, can be found in speakers or headphones to convert electrical signals into sound waves. They are also used in household items such as vacuum cleaner where the motor of a vacuum cleaner uses a powerful magnet to produce high suction. Finally,

they have been used for many centuries in compasses in which a magnetised needle gets rotates to allign with the Earth's magnetic field [6].
Magnets are also used in various ways for research purposes. An example of this is in Earth science, in which magnets are used to measure the magnetic field of the earth, or in space research where magnetic sensors are used in satellites and spacecraft in order to study the magnetic fields of celestial bodies.
Magnets are also used in research at CERN where superconducting magnets are used to steer and focus charged particles, allowing researchers to study fundamental particles and interactions.

2.2 How are magnetic fields generated?

There are generally two distinct methods of generating magnetic fields: using permanent magnets or using electromagnets. These two methods will be accounted for below.

2.2.1 Permanent Magnets

Permanent magnets are magnets that produce their own magnetic fields at all times. The generation of a magnetic field in a permanent magnet is a result of the alignment of electron spins within the material. This property, inherent to electrons, is called "spin" and generates a tiny magnetic moment. This moment is generated when the electron spins align in a preferred direction, creating a magnetic field. The aligned electron spins create a magnetic field that flows from one pole of the magnet to the other, forming a closed loop. The field lines emerge from the magnet's North Pole, loop around the magnet, and reenter through the South Pole. This magnetic field can either attract or repel other magnets or magnetic materials.

2.2.2 Electro-Magnets

Electromagnets are a type of magnet that is created by passing an electric current through wire coil which will generate a magnetic field around the coil. It is possible to control the strength of the magnetic field by either adjusting the current intensity or the number of turns in the coil.
The relationship between this current and the magnetic field that it generates can be defined using Ampere's law which states that the magnetic field around a current-carrying wire forms parallel circles perpendicular to the direction of the current. The strength of the magnetic field is thus directly proportional to the current and inversely proportional to the distance from the wire. Furthermore, as opposed to permanent magnets, the magnetic field of an electromagnet is only present when the current is flowing through the coil. When the current is switched off, the magnetic field disappears [7].
Certain materials such as iron or steel can be used within the coil to enhance to magnetic field by strengthening and concentrating it. Electromagnets are used in many different applications Due to the contractility of the magnetic

field generated by Electromagnets. They can for example be found in electronic equipment, industrial equipment and MRI machine [8].

2.3 Magnet Design

Common magnet designs used in various scientific and engineering applications include dipole, quadrupole, and sextupole magnets. Each design has unique characteristics and functionalities based on their magnetic field configurations:
A dipole magnet has two magnetic poles, a north pole and a south pole, and is the most basic magnet. In a dipole magnet, the magnetic field lines emerge from the north pole and loop back into the south pole which forms a relatively uniform magnetic field along the length of the magnet. It can be used to bend the path of charged particles in particle accelerators, which allows researches to accelerate and steer particles in physics experiments.
A quadrupole magnet consists of two North Poles and two South Poles that are arranged in a symmetrical pattern as seen in fig x. The magnetic field of a quadrupole magnet is focused along two perpendicular axes and weak along the other two axes, resulting in a "focusing" effect on charged particles passing through the magnet. Quadrupole magnets are highly useful in beam focusing and beam shaping in particle accelerators. They help to focus beams which increases beam brightness and improving experimental precision.
Finally a sextupole magnet has six magnetic poles, typically arranged in alternating North and South Poles around the magnet's circumference as seen in fig x. The magnetic field of a sextupole magnet has a more complex shape in comparison with dipole and quadrupole magnets. This complex shape has the goal of correcting greater deviation in the particle beam. Sextupole magnets are mainly used to correct and compensate for nonlinear effects in particle beams. They help to improve beam stability, reduce beam size, and enhance the performance of particle accelerators.

2.4 Resistive Magnets vs. Superconducting Magnets

Superconducting magnets are electromagnets made of superconducting wire, and have to be cooled to cryogenic temperatures while in operation. They are capable of producing intense magnetic fields because the wire surrounding the magnet has no electrical resistance while the magnet is in its superconducting state which enables the magnet to conduct much larger electrical currents [9].
As aforemention, superconducting magnets have to be at cryogenic temperatures in order to become superconducting. It is common to cool the coils in the magnets well below their critical temperature, which for most superconducting magnets is 10K, as they will function better when they are at a lower temperature because they are more able to stand higher currents without returning to their non-superconductive state. There are typically two methods of cooling the coils: Liquid cooling or mechanical cooling. In liquid cooling, the coils are cooled using liquid helium which reaches a temperature far below the critical temperature of the coils. With this method, the magnet and helium is con-

tained in a cryostat in order to preserve the cryogenic temperatures Due to the increasing cost and limited availability of liquid helium, another common way of cooling superconducting magnets is to use a method known as two stage mechanical refrigeration. With this method, two types of mechanical cryocoolers are used to keep the magnets below their critical temperature[10].

Resistive magnets are made using coils of wire made from conductive materials, such as copper. A magnetic field is generated by passing an electric current through these coils, which are often wound around a solid core or a hollow cylinder made of non-magnetic material. Resistive magnets produce a significantly lower magnetic fields strength compared to superconducting magnets. This is because their field strength is limited by the heat generated due to electrical resistance. Resistive magnets also require a continuous power supply in order to maintain their magnetic field, as opposed to superconducting magnets that only require initial energy to cool the coils to their superconductive states, making them highly suitable for experiments with a longer duration [11].
In summary, resistive magnets are more suitable for use cases where moderate magnetic fields are required and continuous power is available, while superconducting magnets excel in generating very high magnetic fields efficiently and are commonly used in advanced scientific research and medical applications.

3 Beam Dynamics

3.1 Charged particles behaviour in magnetic field

A charged particle, such as an electron or a proton, gets effected by a magnetic force when it moves trough a magnetic field. Factors such as the particle's velocity, the direction of the magnetic field and the strength of the magnetic field all have an effect on the particle's behavior in the magnetic field. The magnetic force acting on the charged particle is always perpendicular to both the velocity of the particle and the direction of the magnetic field.
The magnitude of the magnetic force on the charged particle can be defined using the equation which describes the Lorentz force:

$$F = q * v * B * sin(\theta)$$

where:
F is the magnitude of the magnetic force,
q is the charge of the particle,
v is the magnitude of the particle's velocity,
B is the strength of the magnetic field,
θ is the angle between the velocity vector and the magnetic field vector.

The magnetic force is only able to change the direction of the particle's motion but is unable to change the velocity of a charged particle. The way a

charged particle behaves in a magnetic field depends on how the motion of the particle is positioned with respect to the magnetic field. If the charged particle's velocity is perpendicular to the magnetic field lines, the magnetic force acts as a centripetal force, which causes the particle to move in a circular path. The particle's speed remains constant, but its direction continuously changes due to the magnetic force.
If the charged particle's velocity is parallel to the magnetic field lines, the magnetic force does not deviate the particle's path. Thus, the particle continues to move in a straight line without any acceleration due to the magnetic field.
Finally, if the charged particle's velocity makes an angle with the magnetic field lines, the magnetic force acts as a centripetal force, causing the particle to move in a spiral path. The particle's speed remains constant, but its direction changes due to the combined effect of the magnetic force and the original velocity.

3.2 How do we work with millions of particles

Accelerators are used to accelerate and control millions of charged particles. It is important that these particles are managed in an efficient way to achieve specific experimental objectives. There are a few key method used in accelerator physics to handle millions of particles. Once the particles are inside of the accelerator, magnets are used to focus and steer them. As aforementioned, dipole magnets bend the path of a beam of particles while quadrupole magnets gathers the particles by focusing the beam. To accelerate the particles, electric fields along the accelerator switch from positive to negative at a given frequency, which pulls charged particles forwards along the accelerator [12].
A method that is used to optimize the experiments before they start is to conduct particle tracking simulations to track the trajectories of individual particles moving through the accelerator. These simulations make it possible to calculate the particle's position and momentum when it is affected by the accelerator's magnetic and electric fields, and are essential for optimizing the design of the accelerator.
Another method used to handle millions of particles is to use beam instrumentation systems that measure and monitor the properties of the particle beams in real-time. This data can help in adjusting and controlling the accelerator to maintain beam quality

3.3 How do we do particle tracking? (integration methods, matrices, Hamilltonians)

Particle tracking in accelerator physics involves calculating the position and momentum of a particle as it moves through a electromagnetic field. Various methods are used for particle tracking, including numerical integration techniques, matrix-based methods, and Hamiltonian dynamics.
Numerical integration methods approximate the particle's trajectory by approximating the time and iteratively calculating the particle's position and momen-

tum at each time step. There are two general methods for achieving this: Euler's Method and Runge-Kutta Methods. Euler's Method updates the particle's position and momentum based on the values of the forces and fields at the current time step, while the most common variant of Runge-Kutta Methods calculates intermediate values of the position and momentum to refine the approximation [13].
Another method used for particle tracking are matrix-based methods which are used to track particles magnetic and electric fields. These methods are based on matrix transformations that describe how the particle's position and momentum change between different elements of the accelerator. This is done with the use of transfer matrices which are 2x2 matrices that describe the linear transformation of the particle's position and momentum between different elements of an accelerator lattice. By multiplying the transfer matrices of all elements in a sequence, the particle's trajectory can be calculated efficiently [14].
Finally, Hamiltonian dynamics is a powerful mathematical framework used in classical mechanics, including particle tracking. It involves formulating the particle's motion in terms of a Hamiltonian, which is the sum of kinetic and potential energy. The Hamiltonian equations of motion describe the evolution of a particle's position and momentum with respect to time.

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