Beam and detectors

Beamline for Schools 2021

Note

If you have participated in BL4S in the past, you may have read earlier versions of this document. Please note that in 2021 the BL4S experiments will take place at DESY, Hamburg, Germany. The conditions of the beam at DESY are different from what CERN was offering until 2018. Please read this document carefully to understand if your experiment is feasible under the conditions available at DESY.

Preface

All the big discoveries in science have started by curious minds asking simple questions: How? Why? This is how you should start. Then you should investigate, with the help of this document, whether your question could be answered with the available equipment (or with material that you can provide) and the experimental setup of Beamline for Schools at DESY. As your proposal takes shape, you will be learning a lot about particle physics, detectors, data acquisition, data analysis, statistics and much more. You will not be alone during this journey: there is a list of volunteer physicists who are happy to interact with you and to provide you with additional information and advice.

Remember: It is not necessary to propose a very ambitious experiment to succeed in the Beamline for Schools competition. We are looking for exciting and original ideas!

Contents

Introduction

Starting from scratch

When you first meet with your team members, you are not expected to know much about particle physics, particle detectors, readout systems and data analysis, but a high level of curiosity and the will to learn new things will bring you a long way!

The starting point is finding an idea for your experiment. What are you curious about? What would you like to measure?

Then, you should define which detectors and equipment, such as magnets, you will need to extract all necessary information. Read carefully the material available for the Beamline for Schools experiments, and do not hesitate to discuss with an expert.

Once your idea is shaped, you should verify if it is feasible, if we have all the necessary equipment, and if it is precise enough. If you cannot figure it out by yourself, do not hesitate to get in touch with an expert.

Once your idea is defined, and you verified that it is feasible, it's time to design your experiment.

Finally, tell us in your proposal what you would like to measure and how you will do it.

Particle accelerator experiments

There are two types of setups for experiments taking place at particle accelerators: fixed target experiments, the configuration available at DESY for Beamline for Schools, and colliders.

In a fixed-target experiment the physics focus is on the interaction between a beam of accelerated particles and a target at rest. The interaction can happen both if the beam crosses a target or if it passes close to it. The target can be a solid, a liquid or a gas. Such experiments can have the goals to investigate the particle beam itself, its interaction with matter, or even to test new detectors.

In a Collider experiment (like experiments at the Large Hadron Collider (LHC)), accelerated particle beams, protons at the LHC, travel at close to the speed of light before they are made to collide head-on.

Typical equipment

In a typical experiment, commonly used elements to identify or measure the properties[1] of particles are:

[1] Like their path, their energy, or their Momentum.

- Scintillation counters, or scintillation detectors or just scintillators, for recording the passage of a charged particle. These devices answer the question "did a particle pass through?".
- Tracking detectors for measuring the position of an electrically charged particle within the active volume of a detector. They answer the question "where did a particle pass through?"
- Electromagnetic calorimeters for measuring the energy of electrons, positrons and photons. They answer the question "what is the particle's energy?".
- Magnets modify the trajectory of charged particles according to their electric charge and their momentum. Therefore, they can separate particles with opposite charges or, if combined with tracking detectors, they give information about the particle momentum.

These detectors are *electronic* detectors: when a particle goes through them, an analogue electrical signal is produced in different ways. For example, in a Cherenkov detector or a scintillator, light is emitted when a particle goes through and it is converted into an electrical pulse using a Photomultiplier. In a gaseous Tracking chamber, a particle induces the generation of an electric current.

The typical duration of the signals related to the passage of a particle is 100 ns and the voltages induced are typically 100 mV to 1 V. The signals are sent to a readout system where they are converted to a digital value and eventually read out by a computer and stored to a hard disk. In silicon tracking detectors, the electrical pulse is converted to a digital value within the detector itself and the digital signal is read out by a computer.

Examples of detectors in the BL4S experiment are described in more detail in the following chapters. **Keep in mind that you do not need to use all the detectors to build your experiment, and that you can bring your own detector to DESY.**

Trigger and readout

Particle physics experiments produce a large amount of data, and a system is required to decide which data are relevant for the physics we are interested in. This system is known as Trigger and its role is identifying interesting interactions ("events") and instructing the computer to initiate the readout of the data from all the detectors. The trigger is a fundamental and complex component of LHC experiments, where collision rates are very high and only a very small fraction of the collisions are of interest[2].

[2]For example, the production of a Higgs Boson occurs in one out of a trillion events (where one trillion is 10^{12}).

In BL4S, the trigger is much simpler and, typically, it is built using signals from some of the detectors. A triggering system might, for example, require coincident signals from two or more scintillators along the beam path to indicate the passage of a particle. When a trigger occurs, data from all detectors are recorded by the readout system and a signal is sent to a computer that transfers the data to mass storage, usually a disk. This mechanism is very similar to when you take a picture with a digital camera. When the shutter-release button is pressed, information (light) is transferred to the charge coupled device (CCD), converted to digital data, and recorded to memory. One difference is that in the case of BL4S, the exposure time is about 100 ns.

Data Analysis

All the data collected by the different components of an experiment need to be carefully analyzed in order understand their meaning, and access the physics information. A large amount of software has been developed at CERN and elsewhere for the analysis of experimental data. The analysis software is based on a framework called Root, which is used by many physics laboratories all over the world.

The Beam Lines

The BL4S experiments take place at one of the beam lines at the DESY II Test Beam Facility. DESY II is a Synchrotron able to accelerate electrons up to an energy of 6.3 GeV [3]. The electron beam accelerated by DESY II hits a carbon fiber target generating photons, which are then subsequently converted into electrons and positrons of variable energies. This stream of particles is called the Secondary beam or the test beam. You, as the user of the beam line, can choose the charge, the collimation and the momentum of the beam entering the experiment area by adjusting a series of collimators and magnets.

Bending magnets

Bending magnets[4] are used in the beam line to guide the particles in a certain direction, and to choose the particles' momenta by setting the intensity of the magnetic field [5]. A bending magnet is a dipole (Figure 1) with a vertically-orientated magnetic field. The particles that cross the field will be deflected horizontally, according to the Lorentz force.

Collimator

A collimator is a tool used to filter a particle beam. There are two sets of collimators in the beam lines at DESY. The primary collimator defines the Momentum acceptance and Beam divergence. A secondary collimator, placed in the test beam area, allows to further reduce the Beam halo. The flux available is proportional to the collimator settings.

Beam generation details

The beam production at the DESY II Test Beam Facility is sketched in Figure 2. The electron bunches in the DESY II accelerator cross the primary target stations. The

[3]In high-energy physics, the units for energy, momentum and mass are GeV, GeV/c and GeV/c^2, respectively, where c is the speed of light. In the world of particles, these units are more practical than the MKS units. The eV is defined as the energy acquired by an electron accelerated by a potential difference of 1 V: 1 GeV = 1.6×10^{-10} Joule, 1 GeV/c^2 = 1.783×10^{-27} kg. Time is usually measured in nanoseconds (ns), where 1 ns = 10^{-9} s, which is the time it takes for light to move a distance of 30 cm. For comparison, the maximum energy of the Proton beam at the LHC is 6500 GeV/c.

[4]You might consider watching this short instructional video, which shows how charged particles move when influenced by a magnetic field: Particle movement in a magnetic field.

[5]A bending magnet is typically an electromagnet and the intensity of the magnetic field is modulated by the current flowing in it

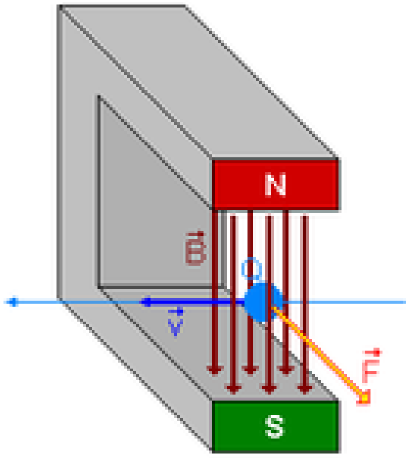


Figure 1: A dipole magnet with the vertical magnetic field and a charged particle moving horizontally into the field. The force is perpendicular to the magnetic field vector and the velocity vector, deflecting the charged particle horizontally. Image source: https://hr.wikipedia.org/wiki/Portal:Fizika/Slika/37,_2007.

primary targets are 7 µm thick carbon fibers put into the beam. Here, Bremsstrahlung photons are produced, and they fly towards a secondary target, called conversion target, consisting of a few mm thick metal plates. When the photons hit this target electron / positron pairs are produced. These particles display a spectrum of energies extending up to 6.3 GeV (the energy of the electrons in the DESY II accelerator). Then they pass a dipole magnet and a collimator behind, that can be tuned in order to choose:

- The particle type: electrons or positrons.
- The particle momentum: any value between 0.5 GeV/c and 6 GeV/c.
- the momentum spread: a typical value for the momentum spread is around 0.15 GeV/c.

The selected particles form the secondary beam, **which will contain either electrons or positrons with a well defined momentum**. The rate of particles in the beam can reach several kHz, depending on the momentum.

As the beam line provides mostly one particle at a time, it lends itself well to experiments that focus on effects that can be seen with individual high speed particles. Experiments that require a high number of particles (e.g. the irradiation of electronics) are more difficult to realize.

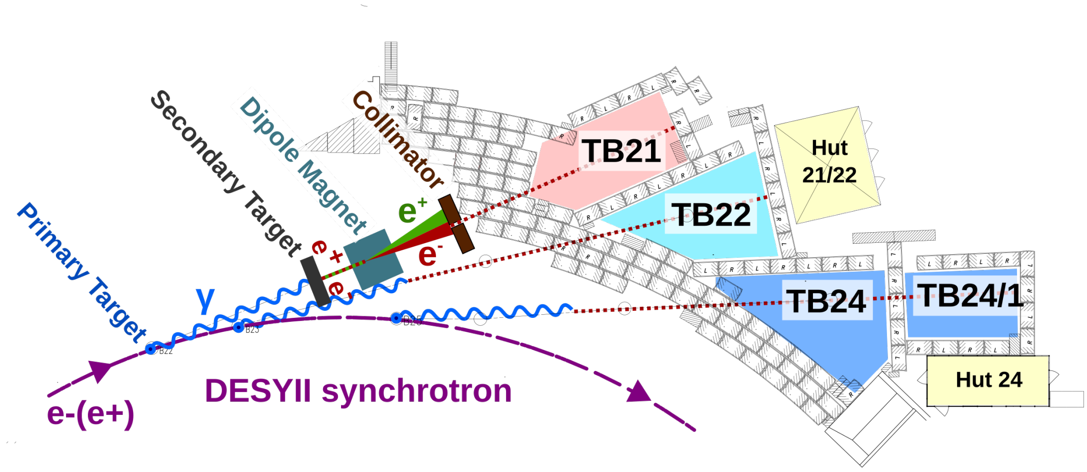


Figure 2: Sketch of the test beam production at DESY II. The text gives detailed information about the various points along the beam-path.

Beam composition

The amount of particles in the beam depends on the selected momentum, the Collimator opening, and the polarity (if they are electrons or positrons). The particle rate can reach up to 10 kHz. Figure 3 shows the typical dependence of the particle rate on the selected particle momentum. For example, if you select a beam momentum of 1 GeV/c, the particle rate is approximately half of the maximum rate. Therefore the beamline will deliver 5000 particles per second when the beam is ON. The negative (positive) beam contains negatively (positively) charged electrons (positrons). It is not possible to have a beam of photons. The particles of test beam are relativistic. This means they are moving at almost the speed of light.

The beam has a more or less round cross section. The beam spot size is driven by the collimators and has a typical dimension of 2 cm $\times$ 2 cm when entering the test beam area. The further away the beam is from the entrance window, the wider it gets.

The amount of background particles (photons, muons, neutrons) generated in addition to the electrons and positrons is negligible. The beam at DESY can be considered a pure electron / positron beam.

Take-home messages about the beam:

- Composed by electrons or positrons.
- Particle momentum up to 6 GeV/c.
- Particle rate maximum of 10 kHz, at approximately 2 GeV/c.
- Beam spot size at the entrance of the test beam of 2 cm $\times$ 2 cm.

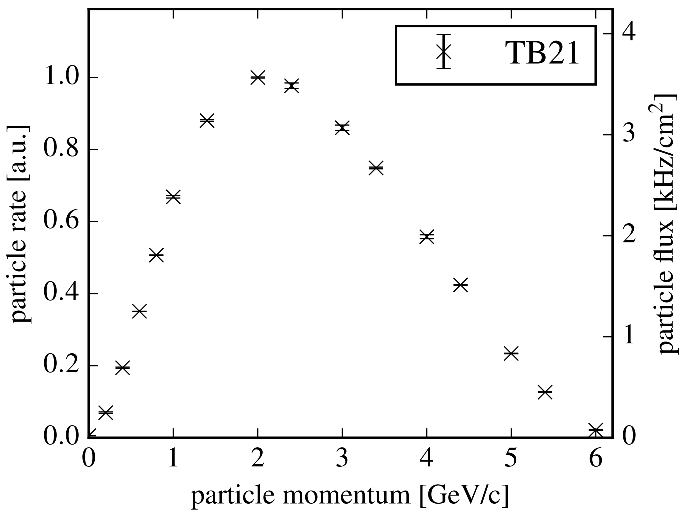


Figure 3: Typical dependence of the beam rate on the selected momentum; in this example measured in area TB21. The rates is normalized to a maximum of 1.0.

The DESY test beam areas

The Beamline for Schools takes place in one of the test beams areas, which have a size of about 5 m × 10 m, where the equipment can be laid out according to the needs of your experiment. Also, depending on the area, there are some fixed installations like two big magnets and beam telescopes (detailed descriptions below). Additionally, it may be possible to install devices that are brought by your team to the experimental area[6]. Each request will be reviewed individually and will need to respect health and safety guidelines. For example, the installation of large amounts of combustible material (e.g. wood) is not possible for safety reasons. It is also not possible to expose any Biological material to the beam.

[6]Please note that CERN and DESY cannot guarantee the installation of all the suggested devices.

The BL4S detectors

Scintillation counter

A scintillator is a material that produces scintillation light, a property of luminescence, when excited by ionizing radiation[7]. Luminescent materials, when struck by an incoming electrically charged particle, absorb some of the particle's energy and scintillate, i.e. re-emit, the absorbed energy in the form of light. A scintillation counter is obtained when a scintillator slab is connected to an electronic light sensor, a device that converts light into an electronic signal, in our case a sensitive Photomultiplier tube. Photomultiplier tubes absorb the light emitted by the scintillator and re-emit it in the form of electrons, via the photoelectric effect [8]. The subsequent multiplication of these photoelectrons results in an amplified, electrical pulse that can be analyzed; yielding meaningful information about the particle that originally struck the scintillator.

Several scintillators are available for installation in the experiment. The scintillators can be used for counting particles or for setting up the trigger logic. Fast scintillators can be used for timing the particles (i.e. measuring the time it takes for a particle to travel from one scintillator to another).

Halo counter

The halo counter is formed by a specific arrangement of scintillators placed around the beam, for example, a set of 4 scintillators that form a hole around the beam passage (Figure 4) or a single scintillator with a hole. Its purpose is to identify particles that are too far away from the beam axis. While a collimator immediately filters the beam by rejecting particles with spread away from the beam axis, the halo counter identifies them and thus makes it possible to choose to either reject or flag them. This is useful, e.g. for flagging particles that interacted with a certain absorber and underwent Scattering.

Delay Wire Chamber (DWC) / Tracker

The Delay Wire Chamber (DWC) is a 2D particle tracker consisting of a multi-wire chamber that can give the coordinates of the position of a particle that passed through the detector. It uses an array of wires kept at high voltage and connected to a delay line. The chamber is filled with gas (a mixture of argon and CO_2). Any Ionizing particle that passes through the chamber will ionize the atoms of the gas. The resulting ions

[7] You can watch a simple animation here:
https://upload.wikimedia.org/wikipedia/commons/2/22/Scintillation_Detector.gif .

[8] The extraction of an electron from a material hit by photons

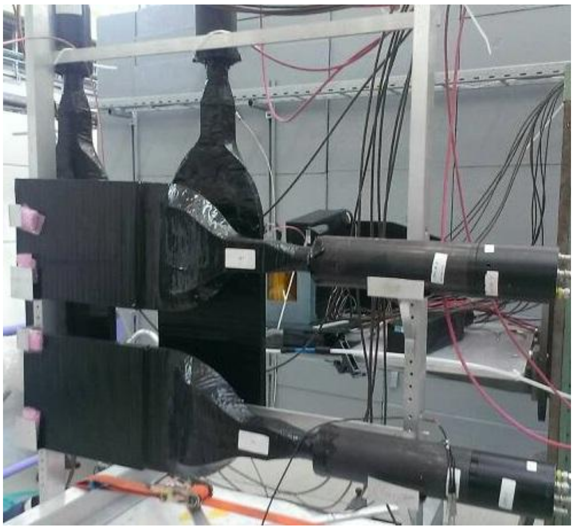


Figure 4: A Halo counter.

and electrons are accelerated by an electric field across the chamber, causing a localized cascade of ionization. The signal from the wires builds up two electric signals in the delay line, one in each direction. By using a reference signal as a common start, and measuring the time delays for the signal to reach each end of the delay line, the impact point —where the first ionizing took place— can be determined.

The active area is 10 cm × 10 cm and position resolutions of 200 µm–300 µm can be achieved. The unit "µm" represents a micrometer, one millionth of a meter. However, the chamber can measure only one particle inside a certain time window of approximately 700 ns, this means that they can track up to $1 \cdot 10^6$ particles per second. Three DWCs are available for the experiment, if required.

MicroMegas detectors / Trackers

MicroMegas detectors serve the same purpose as DWCs; they allow you to track particles. Compared to the DWCs, they have a larger surface and a higher resolution. The disadvantage is that they are not as fast. With the electronics that will be used to read those out, we can at most track 500 particles per second. The MicroMegas detectors have a spatial resolution of about 200 µm and an active area of 40 cm × 40 cm. They are 1D detectors and therefore able to record the position of a charged particle in the vertical or the horizontal plane only. As there are four of them, you can build, by combining two of them, two 2D detectors. The MicroMegas, for example, can be used behind a magnet (for example the BRM described below) to record the angle by which charged particles are deflected in the magnetic field. You may also be able to use them in order to measure the scattering of particles in a target that you install in the beam line.

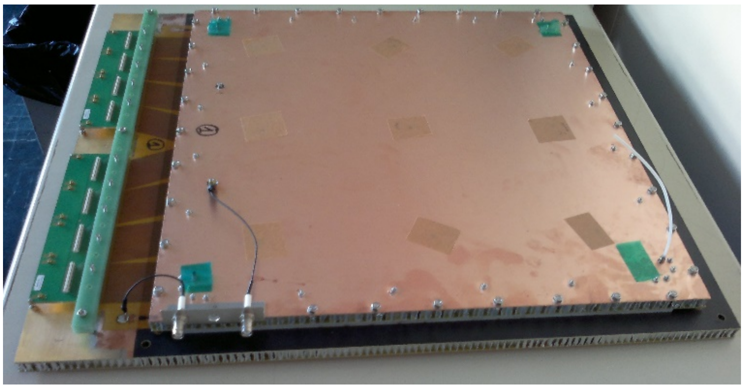


Figure 5: MicroMegas detector.

Silicon Pixel Detectors / Trackers

As the gaseous detectors described above, silicon pixel detectors are used for particle tracking by delivering a 2D information on where a particle has passed through. These detectors work very similarly to nowadays camera chips in mobile phones. When a highly energetic charged particle traverses the chip, it deposits a small amount of energy which is registered as a signal in the pixel cell it traversed.

A few different designs of silicon pixel detectors are available at the DESY II Test Beam Facility, ranging from a few mm to a few cm in size. Their resolution is typically in the order of a few µm.

Beam telescope

For measuring the track of a particle, multiple tracking detectors have to be used. An available, ready-to-use setup of multiple silicon pixel detectors are beam telescopes. A beam telescope typically consists of three to six planes of pixel detectors which are subsequently ordered along the beam axis. Knowing the traversal positions in the pixel matrix in each telescope plane along the particle path, the track of the particle can be identified, which mostly corresponds to a straight line through all the hit pixels of the telescope planes. Knowing the track of a particle allows pointing to the source of the beam — thus, it is historically called telescope as the telescopes used in astronomy. The resolution achievable by a beam telescope is usually in the order of a few µm.

Compared to the DWC and the MicroMegas detector, the telescope has by far the highest spatial resolution and provides therefore the most accurate tracking. The disadvantage is that the sensors of the telescopes have a surface of only 2 cm $\times$ 1 cm.

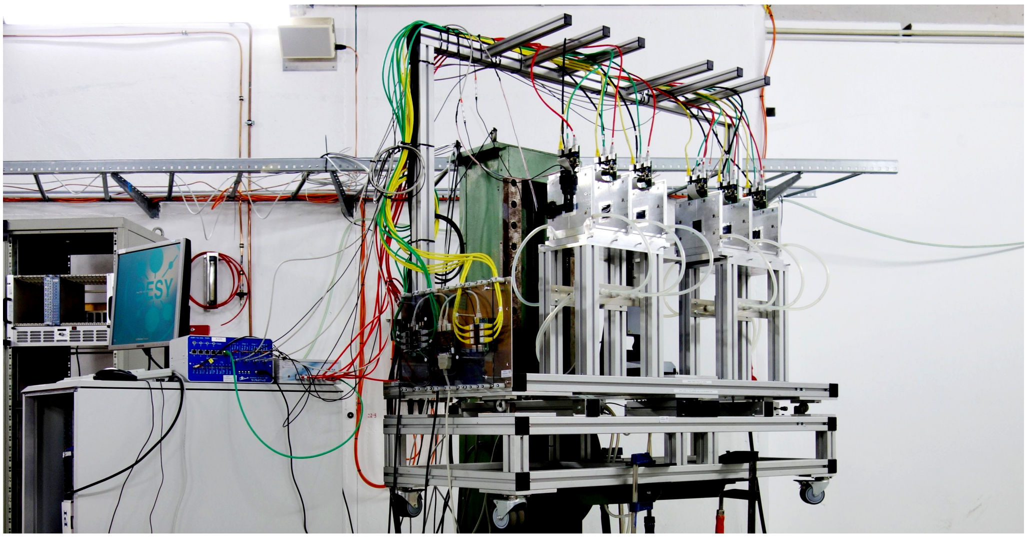


Figure 6: One of the beam telescopes installed at the DESY test beam. Visible are the six layers of the telescope on the right side (square aluminum plates with a black rectangle in the middle) and the readout electronics with the TLU (trigger logic unit) on the left side.

Time of flight measurements

In some cases it may be important to know the velocity of a particle. This can be done by measuring the time of flight over a known distance. Two scintillators or other detectors record the time at which the particle is seen at a defined location. By recording the time difference and the distance between the detectors, the velocity can be calculated. Note that the distance between the detectors can be measured to an accuracy of 1 cm and the time to 200 pico seconds.

Lead crystal calorimeter

A lead crystal Calorimeter is a detector that measures the energy of impinging particles (therefore it is not a Tracking detector). An electron hitting the calorimeter will produce a fully contained Electromagnetic shower, depositing all its energy in the calorimeter and thus allowing a measurement of its energy. By measuring the deposited energy, the energy of the incoming particle can be measured. Beamline for Schools has 16 calorimeters, each having a volume of 10 cm $\times$ 10 cm $\times$ 37 cm (Figure 7).The energy resolution, σ_E, of the calorimeter is estimated, at energy E, as:

$$\frac{\sigma_E}{E} = 0.02\% + \frac{6.3\%}{\sqrt{E}}$$

Figure 7: Stack of lead crystal calorimeters.

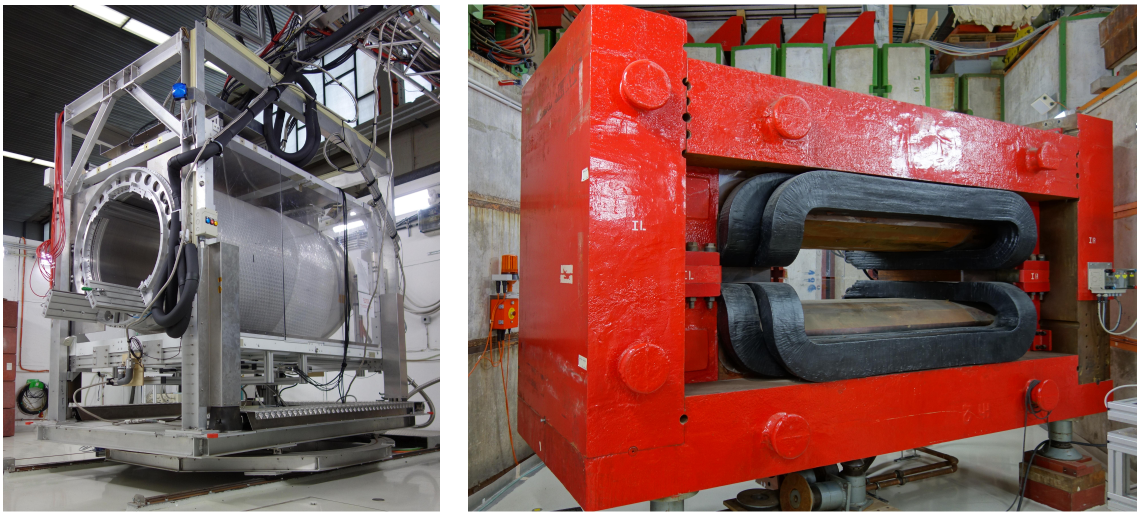
Additional Equipment

BRM dipole magnet and PCMAG solenoid

At the DESY test beam, two large magnets are available.

One is a superconducting solenoid magnet with a field of up to 1 T, called PCMAG, installed in area TB24/1 (Figure 8a). It can house detector setups of diameters up to 77 cm, which are supported inside the magnet on two rails. Along the magnet axis, which is perpendicular to the beam direction, the field is homogeneous within a few percent along a range of about 60 cm. This magnet is mounted on a movable stage, so it can be moved relative to the particle beam to allow for measurements at different places inside the installed detector. In addition, it can be rotated with respect to the beam direction between −45° and 45°.

The second magnet is a normal conducting dipole, called Big Red Magnet (BRM), with a field up to 1.35 T installed in area TB21 (Figure 8b). It has an integrated length of about 1 m and an opening that is about 1.5 m wide and 0.35 m high.



(a) PCMAG (b) BRM

Figure 8: Left, a): PCMAG, 1 T solenoid magnet mounted on a movable stage. Right, b): BRM, 1.35 T dipole magnet.

Other infrastructure

The test beam areas at DESY are equipped with a laser alignment system which simplifies putting the setup in the exact beam location. Also, a huge collection of so-called NIM modules (multipurpose electroni modules) are available for simple signal processing and trigger generation. Additional electronic modules for the read-out of the detectors as well as associated software will be provided by CERN. We do not expect you to design the read-out system of your experiment. This will be done by experts of DESY and CERN for the winning proposals.

Data Acquisition

BL4S will provide a complete data acquisition system for reading out the detectors and controlling the experiment. This system is fast enough to trace up to 2000 particles per second.

The data acquisition system provides tools for the on-line monitoring of the experiment in the form of histograms.

Don't worry about the details of this system. Experts of CERN and DESY will help the winners of BL4S to set-up the system and will also provide code for and assistance with the analysis of your data.

Glossary

Beam divergence The widening of the beam along its path. 7

Beam halo The cloud of particles surrounding the main beam in an accelerator. 7

Biological material Living cells, human / animal tissue. 10

Boson Particles can be categorized as bosons or fermions according to their intrinsic spin. 5

Bremsstrahlung An electromagnetic radiation produced by the deceleration of a charged particle when deflected by another charged particle. See also: Wikipedia:Bremsstrahlung. 8

Calorimeter A detector that measures the energy of a particle. 5, 14

Cherenkov detector A gas volume that emits light when it gets penetrated by charged particles. The light emission depends on the type of particle and its momentum. Wikipedia: Cherenkov detector. 5

Collider An accelerator that collides two beams which are cruising in opposite directions as in the LHC. 4

Collimator A device to limit spatial width of the beam perpendicular to its direction of flight. See also: Wikipedia: Collimator. 7, 9

Electromagnetic shower An avalanche of particles created from the interaction of a high-energetic particle with the material of a calorimeter. 14

GeV, Electronvolt A unit of energy used in particle physics 7

GeV/c A unit of momentum used in particle physics. 7

GeV/c^2 A unit of mass used in particle physics. 7

Ionizing particle A particle with enough energy to knock out electrons of atoms or molecules. 11

MicroMegas Micro-MEsh Gaseous Structure, a particle detector amplifying ionization signals in a gas volume. See also: Wikipedia: MicroMegas. 12

MKS units Units expressed in meters, kilograms and seconds. 7

Momentum Product between the mass of a particle and its velocity. For a relativistic particle (speed close to that of light) one should consider the increase in the particle mass defined by the Lorentz factor: γ: $\mathbf{p} = m \cdot \gamma \cdot \mathbf{v}$, where m is the particle mass, γ the Lorentz factor defined as $\gamma = \frac{1}{\sqrt{1-v^2/c^2}}$ and $\mathbf{v}$ the speed vector. 4

Momentum acceptance Particles with this range of momentum will pass through. 7

Muon, µ A particle like an electron but much heavier and not stable (decays into other particles). 9

Photomultiplier A device that converts photons into electric signals. 5, 11

Positron, e^+ An elementary particle that is the antimatter twin of the negatively charged electron; this means both have the same properties, but the positron is positively charged. 7

Proton A proton is a subatomic particle, with a positive electric charge. 7

Root A powerful software framework for the display and analysis of physics data. 6

Scattering An interaction between two particles that changes the particle energy and momentum. Depending on the properties of the scattering process, this leads to the generation of new particles (inelastic scattering), or simply to a deflection and energy loss for the initial particle (elastic, or multiple scattering). 11

Scintillation counter A transparent material that emits light when penetrated by charged particles. 5, 11

Secondary beam Particles created from the interaction of the primary beam with a target. 7

Synchrotron A specific type of particle accelerator, in which the particles are accelerated and fly along a circular path. See also: Wikipedia: Synchrotron. 7

Tracking The measurement of the trajectory of a particle. 5, 14

Trigger It identifies interesting interactions ("events") and instructs the computer to initiate the readout of the data from all the detectors. 5