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Beam and detectors

Beamline for Schools 2020

Note

If you have participated in BL4S in the past, you may have read earlier versions of this document. Please note that in 2020 the BL4S experiments will take place at DESY, Hamburg, Germany. The conditions of the beam are different between the two facilities and are different from what CERN was offering until 2018. Please read this document carefully to understand if your experiment is feasible under the new conditions.

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 particle beams 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

The Beamline for Schools

There are two types of setups for experiments with elementary particles: collider and fixed target configurations. In a Collider experiment (like experiments at the Large Hadron Collider (LHC)), accelerated particle beams travel at close to the speed of light before they are made to collide. In a fixed-target experiment, a beam of accelerated particles collides with a target at rest, which can be a solid, liquid, or gas. The Beamline for Schools (BL4S) experiment is of the fixed target type.

The BL4S experiments will take place at one of the beam lines at the DESY II Test Beam Facility in Hamburg.

Typical equipment

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

- Scintillation counters, or scintillation detectors or just scintillators, for recording the passage of a charged particle,
- Tracking detectors for measuring the position of a charged particle within the active volume of a detector,
- Electromagnetic calorimeters for measuring the energy of electrons, positrons and photons,
- Magnets to enable measuring the momentum of charged particles[2].

These detectors are *electronic* detectors: when a particle interacts with the detector, an analogue electrical signal is produced in different ways. In a Cherenkov detector[3] or a scintillator, light is emitted and converted into an electrical pulse using a Photomultiplier. In a gaseous Tracking chamber, ionization of the gas generates electrons that are multiplied in electric fields. The typical duration of the signals is 100 ns and the signal voltages are typically 100 mV to 1 V. The signals are sent to a readout system where they are digitized and eventually read out by a computer and stored to a hard disk. In solid-state detectors like silicon sensors, the particle generates electron / hole pairs along its trajectory. The generated charge is usually on the

[1] Like their path or momentum.

[2] Bending magnets have to be used together with tracking detectors. The bending angle of a particle that passes though a certain magnetic field is inversely proportional to its momentum.

[3] Cherenkov detectors are not available at DESY and are mentioned here as an example since they were available prior when the competition took place at CERN

level of 20 000 electrons or less and is collected at the edge of the sensor. The signal is then digitized close to the sensor and readout by a computer.

Examples of detectors in the BL4S experiment are described in more detail in the following chapters. It should be emphasized that experiments can be conducted without making use of all of these detectors.

Trigger and readout

Signals from some of the detectors are used to build the Trigger. The trigger logic identifies interesting interactions ("events") and instructs 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[4]. In BL4S, the trigger is much simpler and 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, data (light) is transferred to the charge coupled device (CCD) and recorded to memory. One difference is that in the case of BL4S, the exposure time is about 100 ns.

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.

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

The Beam Lines

General

Bending magnets

Bending magnets[5] are used in the beam line not only to guide the particles in a certain direction, but also to choose the particles' momenta by defining the magnet currents accordingly. A bending magnet is a dipole (Figure 1) with a vertically-orientated magnetic field. The particles that cross the field will be deflected horizontally.

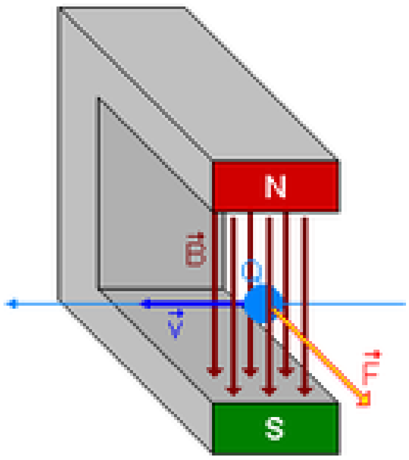


Figure 1: A dipole magnet with the vertical magnetic field and a charged particle moving horizontally into the field. The force is perpendicular to the magnetic field vector and the velocity vector, deflecting the charged particle horizontally. Image source: https://hr.wikipedia.org/wiki/Portal:Fizika/Slika/37,_2007.

Collimator

A collimator is a tool used to filter the beam of particles. There are two sets of collimators in the beam lines at DESY. The primary collimator is movable in both x and y and defines the Momentum acceptance and Beam divergence. A secondary collimator in the test beam area allows to further reduce the Beam halo. This is realized as a lead inset with openings from 2 mm × 2 mm to 50 mm × 50 mm. The flux available is proportional to the collimator openings.

[5]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.

DESY II Test Beam Facility

Beam generation

The beam production at the DESY II Test Beam Facility is sketched in Figure 2. Inside the DESY II accelerator, the electron bunches with a beam energy of up to 6.3 GeV cross the primary target stations. The primary targets placed in the electron beam are 7 µm thick carbon fibers, at which Bremsstrahlung photons are produced. These photons move towards a secondary target, also called conversion target, consisting of metal sheets of a few mm thickness. When the photons hit this target, electron / positron pairs are produced. These particles exhibit a spectrum of energies extending up to 6.3 GeV/c. Then they pass a dipole magnet with a collimator behind. By modifying the magnetic field in the dipole and the collimator opening the following parameters can be chosen:

- The particle type of the beam
- The momentum of the beam
- The momentum spread of the beam

The momentum can be set to any value between 0.5 GeV/c and 6 GeV/c. These selected particles form a beam, the so-called secondary beam, *which will contain either electrons or positrons with a well defined momentum*. This secondary beam consists of mainly single electrons or positrons at rates of up to several kHz, depending on the chosen momentum[6].

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 particles. Experiments that require a high number of particles (e.g. the irradiation of electronics) are more difficult to realize.

Beam composition

The amount of particles in the beam depends on the selected momentum, the Collimator opening and the polarity. 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 relative particle rate is approximately 0.5. Therefore the beamline will deliver around 5000 particles

[6] 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 the MKS units: 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.

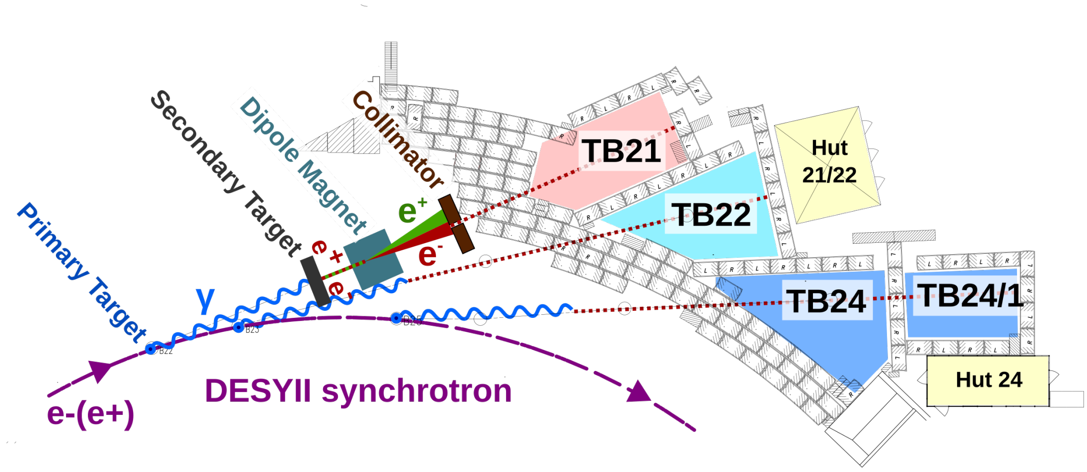


Figure 2: Sketch of the beam production at the DESY II Test Beam. The text gives detailed information about the various points along the beam-path.

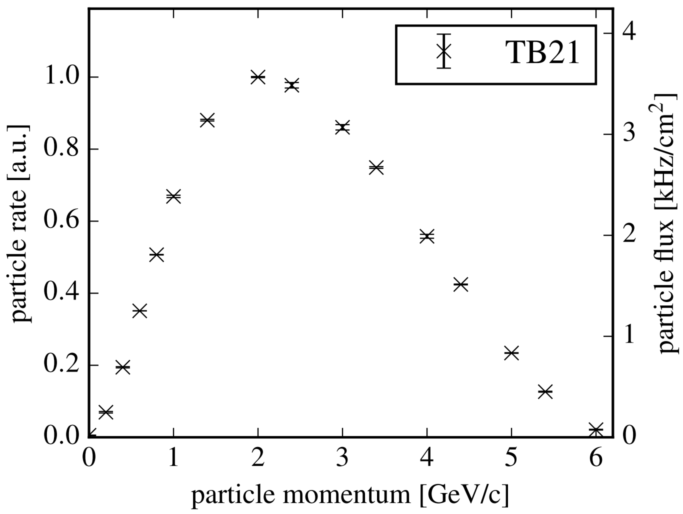


Figure 3: Typical dependence of the beam rate on the selected momentum; in this example measured in area TB21. The rate is normalized to a maximum of 1.0.

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 the beam are relativistic. This means they are moving at almost the speed of light.

The beam provided by DESY II is pulsed due to the DESY II cycle of 80 ms[7]. There is one pulse every 80 ms. The duration of a pulse depends on the selected particle momentum and varies between 20 and 40 ms.

The initial beam has a more or less round cross section with a typical dimension of 2 cm $\times$ 2 cm when entering the beam area. The final beam spot size and its shape are driven by the collimators and can be modified. 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.

The DESY test beam areas

The Beamline for Schools experiments are performed in one of the test beams areas, which have a size of about 5 m $\times$ 10 m, where the available 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[8]. 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.

[7] A period in which DESY II ramps from 450 MeV to 6.3 GeV and back to 450 MeV again.
[8] 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[9]. Luminescent materials, when struck by an incoming 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, 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. 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 one or more scintillators and is defined by how these scintillators are used. 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 a larger angle, 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. The opening of the BL4S halo counter with 4 scintillators can be adjusted between 1 cm and 15 cm.

Delay Wire Chamber (DWC) / Tracking chamber

The Delay Wire Chamber (DWC) is 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 at high voltage 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 and electrons are accelerated by an electric field

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

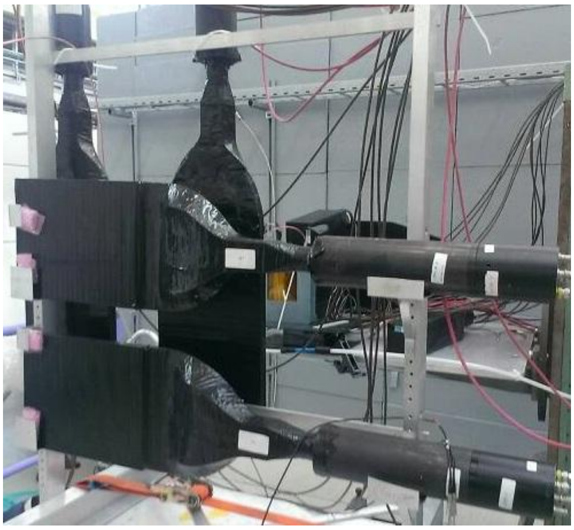


Figure 4: A Halo counter.

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 signals 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. Three DWCs are available for the experiment, if required.

MicroMegas detectors / Tracking chamber

MicroMegas detectors serve the same purpose as DWCs; they allow you to track particles. They are "better" than the DWCs because they have a larger surface and a higher resolution. 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. 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 (such as the BRM; see 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.

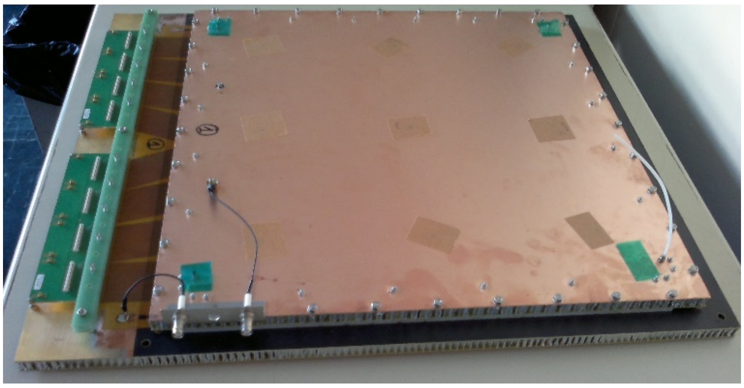


Figure 5: MicroMegas detector.

Beam telescopes

A beam telescope can measure the track of a particle to a high precision. 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 telescope is usually in the order of a few µm.

A beam telescope consists mostly of six, but at least of three detector planes which are subsequently ordered along the beam axis. Each plane has a sensitive silicon pixel chip similar to nowadays camera chips in mobile phones. If a highly energetic charged particle will go through the chip it will deposit a small amount of energy which is amplified in the sensor and results in a signal in the corresponding pixel cell. Knowing the positions in the pixel matrix in each telescope plane, the track of the particle can be identified which corresponds mostly to a straight line through all signal pixels of the detector planes.

A typical application is placing three planes each before and after a sample under test. This sample can be a position resolving detector, such that the beam telescope with its very high precision is used as reference detector, measuring the impact position of a particle at this detector. This allows to compare the signals in a detector under test with the known impact position. Another application for these detectors is the measurement of the scattering angles of the particles caused by the sample. By recording tens of millions[10] of particle tracks a scattering image can be obtained, illustrating the material budget of the sample. Thus, a beam telescope can record images similar to an X-ray machine, but using electrons instead of photons. Compared to the DWC and the MicroMegas detector, the telescope has by far the highest spacial 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.

[10]With the particle rates at the DESY II test beam, recording these events can take several hours.

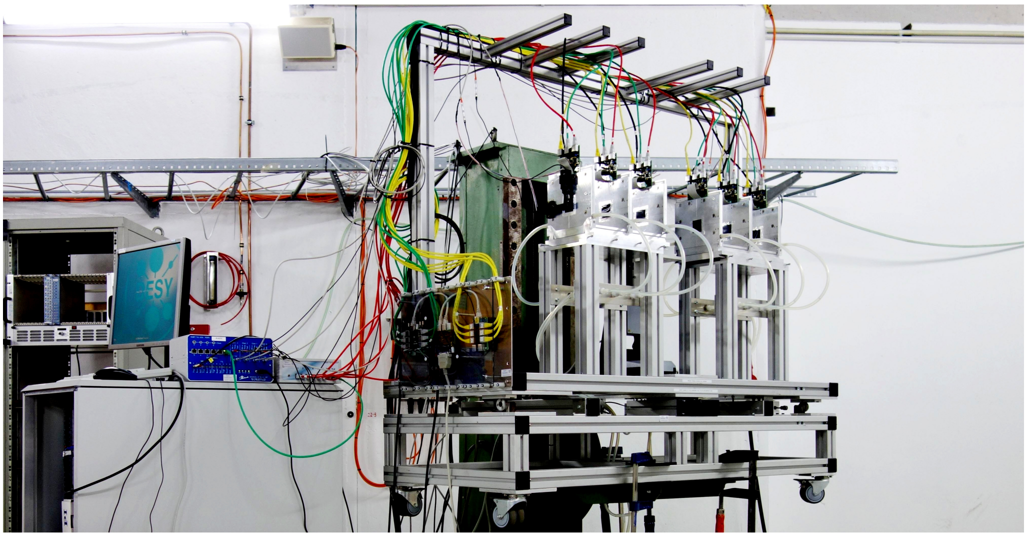


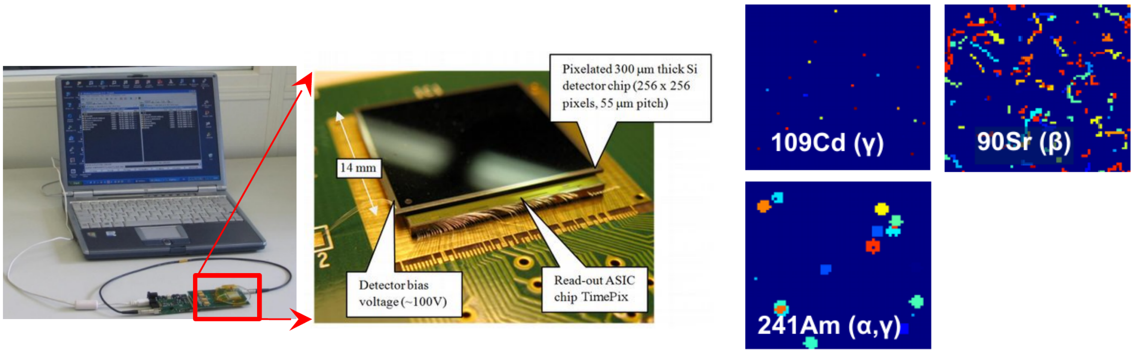
Figure 6: One of the beam telescopes installed at the DESY test beam. Visible are the six layers of the telescope on the right side (square aluminum plates with a black rectangle in the middle) and the readout rack with the TLU (trigger logic unit) on the left side.

Timepix detector

The Timepix chip is designed as a universal readout chip for various types of radiation. It can be used in combination with a pixelated semiconductor detector with a gaseous detector Time Projection Chamber (TPC) or without any sensor (electro-statically collecting electrons)[11].

The available device consists of a semiconductor detector chip bump-bonded to the readout chip. The detector chip is equipped with a single common backside electrode and a front side matrix of electrodes (256 $\times$ 256 square pixels with a pitch of 55 µm).

[11]See also these videos: Medipix 2 - See Through Science and Material resolving CT using Timepix



(a) (b)

Figure 7: The timepix Pixel detector:
a) This device consists of two chips connected by the bump-bonding technique. The upper chip is a pixelated semiconductor detector (usually silicon), the bottom one an ASIC readout.
b) Sample ToA data from Timepix, Top left: gamma photons (dots), Top right: beta particles (squiggles), Bottom left: mixed field of gammas (dots) and alphas (blobs).

Each Timepix pixel can work in one of three modes:

1. Medipix mode — The counter counts the incoming particles.
2. Timepix mode or ToA (Time of arrival mode) — The counter works as a timer, measuring time of the particle detection. This mode distinguishes between particles and / or reconstructs tracks of particles.
3. Time over threshold (TOT) mode — Measurement of the amount of deposited charge in each pixel.

The chip can deliver up to 1000 frames per second. Usually, this kind of device is used for particle Tracking.

Multi Gap Resistive Plate Chamber (MRPC)

Our three MRPC detectors have a surface area of 30 cm × 30 cm. They provide, like the DWCs, Tracking information but with a much smaller resolution. Their main advantage is that they can provide very accurate time information for the passage of a particle. In a well-calibrated system, values as low as 100 ps[12] can be reached. Therefore, the MRPCs are very useful detectors for time-of-flight measurements.

The MRPC consists of a stack of resistive plates, where spacers between these plates define a series of gas gaps. Anode and cathode electrodes are placed on

[12] Where ps stands for pico second, one trillionth of a second.

the outer surfaces of the outermost resistive plate while all interior plates are left electrically floating. The resistive plates are transparent to the fast signals generated by the avalanches inside each gas gap. The induced signal on the external electrodes is the *sum* of the activities of *all the gaps*. You can use the MRPCs to check if the electrons or positions are really traveling at the speed of light.

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 or positron hitting the calorimeter will produce a fully contained Electromagnetic shower, depositing all its energy in the calorimeter and thus allowing a precise measurement of its energy. By measuring the deposited energy, the energy of the incoming particle can be determined. The 16 available calorimeters each have a volume of 10 cm $\times$ 10 cm $\times$ 37 cm (Figure 8). The energy resolution of the Calorimeter is estimated to be:

$$\frac{\sigma_E}{E} = 0.2\% + \frac{6.3\%}{\sqrt{E}} \tag{1}$$

Figure 8: Stack of lead crystal calorimeters.

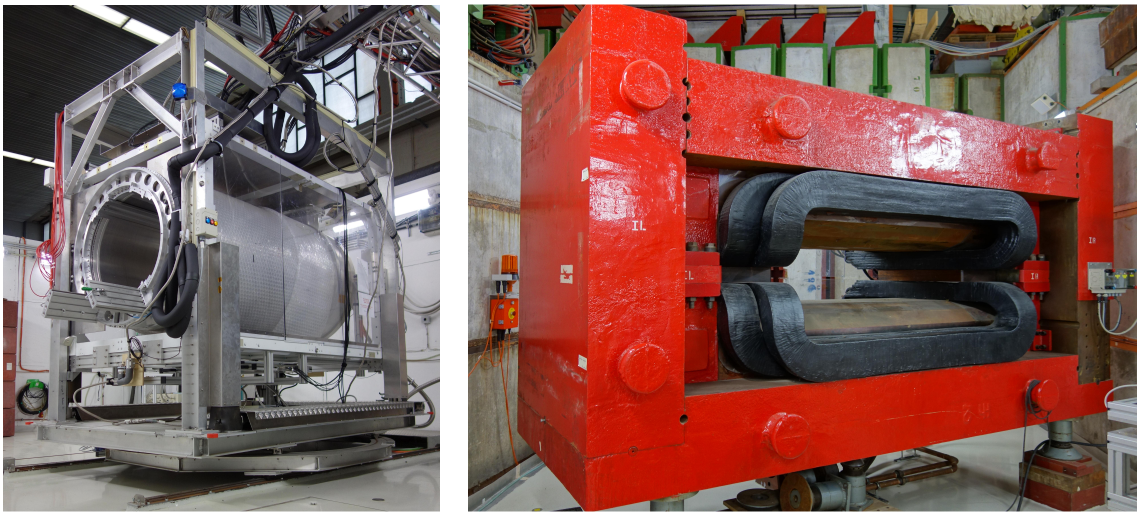
Additional Equipment

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 9a). 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, its angle to the beam direction can be set from −45° to 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 9b). 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 9: Left, a): PCMAG, 1 T solenoid magnet mounted on a movable stage. Right, b): BRM, 1.35 T dipole magnet.

Other infrastructure

The areas at DESY also provide a laser alignment system which simplifies putting the setup in the exact beam location. Also, a huge collection of so-called NIM modules are available which can be used 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. 6
Beam halo	The cloud of particles surrounding the main beam in an accelerator. 6
Biological material	Living cells, human / animal tissue. 9
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. 7
Calorimeter	A detector that measures the energy of a particle. 4, 15
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. 4
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
Electromagnetic shower	An avalanche of particles created from the interaction of a high-energetic particle with the material of a calorimeter. 15
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. 10
MicroMegas	Micro-MEsh Gaseous Structure, a particle detector amplifying ionization signals in a gas volume. See also: Wikipedia: MicroMegas. 11

MKS units	Units expressed in meters, kilograms and seconds. 7
Momentum acceptance	Particles with this range of momentum will pass through. 6
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. 4, 10
Pixel detector	A tracking detector with a 2-dimensional array of sensors; usually made from silicon. 14
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. 5
Scintillation counter	A transparent material that emits light when penetrated by charged particles. 4, 10
Tracking	The measurement of the trajectory of a particle. 4, 14, 15
Trigger	It identifies interesting interactions (“events”) and instructs the computer to initiate the read-out of the data from all the detectors. 5