



Beams and detectors

Beamline for Schools 2027



Contents

Introduction	3
Starting from scratch	3
Physics experiments at particle accelerators	4
Commonly used units	5
Commonly used equipment	5
Exemplary experimental setup	6
Data acquisition	7
Data Analysis	8
Beamlines	9
Beam properties at DESY	9
Beam composition and intensity	9
The experimental area at DESY	10
Beam production (optional reading)	10
Beam properties at ELSA (The University of Bonn)	11
Beam conditions	12
Detectors	13
Magnets	14
TDAQ system	14
Beam properties at CERN	14
Beam composition and intensity	14
The experimental area at CERN	16
Take-home messages about the beam	16
Bending magnets	17
The big red dipole magnet at DESY	17
Magnets at CERN	17
Collimators	18
The BL4S detectors	20
Basic principles of particle detection	20
BL4S detectors of type (1)	22
Beam telescopes	22
BL4S detectors of type (2)	24
Scintillation detectors	24
Lead glass calorimeter	26
YAG screen and camera	28
Glossary	29



Introduction

Beamline for Schools (BL4S) is a physics competition for high-school students from all around the world organised at CERN, the European Laboratory for Particle Physics, in Geneva, Switzerland, DESY, the German Electron Synchrotron, in Hamburg, Germany and the University of Bonn, Germany. Teams of high school students can propose an experiment that they want to perform at a beamline, that is, a part of a particle accelerator.

In **2027** there will be five winning teams. Two teams will perform their experiments at CERN, two teams will be invited to DESY, and one team will be hosted by the University of Bonn. The organisers of BL4S will decide which winning team goes where to make sure that each team will be assigned to the laboratory that best matches the requirements of their proposal.

In this document, you will learn more about the properties of the **beams at CERN, DESY and Bonn** and the **detectors and instruments available for your experiments**.

Important information

In 2027 and 2028, the PS accelerator at CERN will be turned off for maintenance. We will instead use the **CLEAR accelerator**. Details can be found below. CLEAR is, like DESY-II and ELSA, an electron accelerator. This means that in 2027 and 2028, CERN, DESY and the University of Bonn can only provide beams of electrons and positrons. There are no hadrons (protons, pions, kaons) or muons. Please propose only experiments that can be realised with an electron or a positron beam. This may sound like a limitation, but it is an opportunity as well. CLEAR provides a very high beam intensity and enables you to conduct experiments that have not been feasible until now.

Please note also that some of the detectors that you may be used to (e.g. the DWCs at CERN) are temporarily not available because they are not compatible with the CLEAR accelerator and its experimental area. The **BL4S example experiments** document has been updated to only contain ideas for experiments that can be realised with the beams and detectors that are available.

Starting from scratch

When you first meet with your team members, you don't need to know much about particle physics, detectors, data acquisition or analysis. Your curiosity and your wish to learn new things will bring you a long way!

For designing your experiment, your first steps are to understand how particle physics experiments at accelerators typically work and to find an interesting research idea for you. *What are **you** curious about? What would **you** like to learn more about?*



It is not necessary to propose a very ambitious experiment to succeed in the BL4S competition. We are looking for experiment proposals that are creative and feasible and that follow a scientific method. Get inspired by the proposals of the previous winners and by the document listing the [BL4S example experiments](#). This document provides you with short descriptions of different experiments that you could conduct with the beam and detectors available for BL4S. **We encourage you to use them in your proposals!**

Once you have an experiment idea, investigate - with the help of this document - whether it is feasible: *Could the experiments be conducted with the beam and detectors available for BL4S or with material that you can provide? Are the detectors precise enough? What problems could compromise the measurement, and what are possible solutions to overcome them?*

We encourage you to reach out for support to experts in your local university and to the [BL4S contact people](#) from all over the world who are happy to interact with you and to provide you with additional information and advice.

Finally, tell us in your proposal your research idea, what parameters you would like to measure, how you will do it, which problems you might encounter, and how you suggest overcoming potential problems. The evaluation of your experiment proposal will take into account the following criteria:

- Motivation to participate in BL4S
- Motivation of the experiment
- Scientific method
- Feasibility of the experiment
- Creativity of the experiment

Physics experiments at particle accelerators

Particle accelerators can accelerate electrically charged particles, such as electrons, protons or different ions. Acceleration means to change the speed or the direction of movement of the particles. When a particle's speed is increased, its energy is also increased. Usually, particle accelerators accelerate many particles at the same time. We call all these particles together the **beam**. That is, the term "beam" refers to a large number of particles moving in the same direction. There are two types of experimental setups possible at particle accelerators: **fixed-target experiments** or **collision experiments**.

In a **fixed-target experiment**, the physics focus is on the interaction between the beam (i.e. a large number of particles moving in the same direction) and a target at rest. The interaction can happen when the beam moves through a target or



when it moves very close to it. The target can be a solid, liquid or gaseous material. Fixed-target experiments can have multiple purposes: investigating the beam itself, its interaction with matter or testing out a new detector. Fixed-target experiments happen at so-called **beamlines**. The term "beamline" refers to a straight section of a particle accelerator leading the particles to an experimental area. Each beamline can host one or more experiments and has specific properties that need to be taken into account when designing an experiment.

In a **collision experiment**, the physics focus is on the interaction between two beams. These beams travel in opposite directions at nearly the speed of light before colliding with each other, for example, at the [Large Hadron Collider \(LHC\)](#).

In Beamline for Schools, you can only conduct fixed-target experiments with different types of electrically charged particles (see [Beamlines](#)). *Please consider this when designing your experiment.*

Commonly used units

Particle physicists often use units other than the SI units Joule and Kilogram to express energies or masses. In particle physics, **energies** are given in the unit electron-volt, short **eV**, which is the product of the elementary charge e and the unit of voltage V . The eV is defined as the energy gained by one electron accelerated by a potential difference of 1 V. For example, the maximum energy of the protons accelerated in the LHC is 6800 GeV, where $1 \text{ GeV} = 1 \times 10^9 \text{ eV} = 1.6 \times 10^{-10} \text{ Joule}$.

Moreover, particle **masses** are given in the unit eV/c^2 , where c is the speed of light (i.e. the speed of photons). For example, the mass of electrons is $511 \text{ keV}/c^2$, the mass of protons is $938 \text{ MeV}/c^2$, and the Higgs boson mass is $125 \text{ GeV}/c^2$, where $1 \text{ GeV}/c^2 = 1.783 \times 10^{-27} \text{ kg}$. This unusual unit makes it much easier to know how much collision energy is needed to create a certain type of particle. For example, a collision energy of at least 125 giga-electronvolts (GeV) is needed to create one Higgs boson.

The unit for **momentum** is eV/c . Note that physicists often talk about momentum instead of energy. Luckily, you can rather easily convert momentum to energy and vice versa using the speed of light (c).

Time is usually measured in nanoseconds (ns), where $1 \text{ ns} = 10^{-9} \text{ s}$, which is the time it takes for photons to move a distance of 30 cm.

Commonly used equipment

Several devices are used to detect and identify particles, and to measure their properties (e.g. trajectory or energy). Commonly used devices are:



- **Scintillation detectors** are used to detect electrically charged particles. Whenever such a particle passes through the scintillation detector, you get an electric signal. Scintillation detectors answer the question **"did a particle pass through?"**.
- **Trackers** are 2D or 3D (two- or three-dimensional) detectors. Hence, they measure the position of an electrically charged particle within the sensitive area of the detector. They answer the question **"where did a particle pass through?"**.
- **Magnets modify the trajectory of electrically charged particles** according to their electric charge and their velocity (Lorentz force). Therefore, they can separate particles with opposite electrical charges or, if combined with tracking detectors, give information about a particle's momentum. Hence, magnets are usually used together with trackers.
- **Electromagnetic calorimeters** measure the energy of electrons, positrons, and photons. They answer the question **"what is the energy of the particle?"**.

Please note that no detector is perfect. The detectors will even give you signals when no particle passes through. We call this "noise". One way of eliminating noise is to combine the signals of two detectors in a **coincidence module**. **You do not need to use all the above-listed detectors to conduct your experiment.** You can also bring your own detector, if required for your experiment.

Exemplary experimental setup

Figure 1 shows an example of the experimental setup of a fixed-target experiment at a beamline, particularly the setup of the **"Teomitzli Team"**, one of the winners of the 2021 edition of BL4S at DESY. The goal of their experiment was to test a Cherenkov detector that they had designed. First, the incoming beam (coming from the right-hand side of the picture) passes through a scintillation detector that can indicate that a particle passed through (1.); then, through two trackers that can indicate where a particle passed through (2.); followed by the newly designed detector that the team wanted to test (3.); another pair of trackers that can indicate where a particle passed through (4.); and through another scintillation detector that can indicate that a particle passed through (5.). Both scintillation detectors combined in a **coincidence module** are used to generate the **trigger** signal for the data acquisition, making sure that only particles that passed through the full setup are considered.

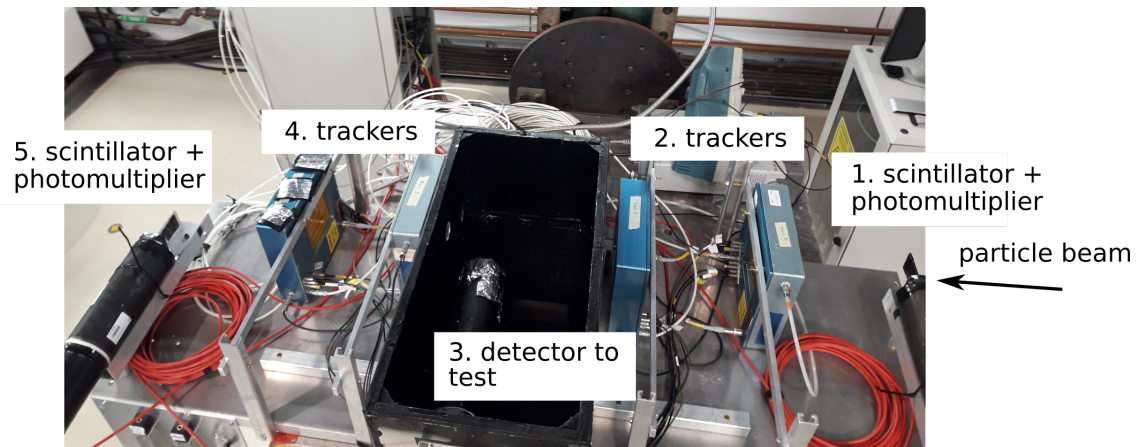


Figure 1: The experimental setup of one of the winning teams of the 2021 edition of BL4S, the "Teomitzli team". The beam comes from the right-hand side. First, it crosses a scintillator (1.); then, 2 trackers (2.); and the newly designed detector (3.). Finally, it crosses another pair of trackers (4.) and another scintillator (5.).

Data acquisition

When an electrically charged particle passes through a detector (e.g. scintillator), an analogue electrical signal (e.g. a voltage or a charge) is generated (see [Basic principles of particle detection](#)) and transformed into a digital signal by means of some special electronic modules. These signals are the data that we want to analyse. Particle physics experiments produce a huge amount of data. Hence, a data acquisition system is required to decide **which data should be read out**. Ideally, only the data relevant to the physics phenomenon you are interested in (i.e. the data you need to answer your research questions) is read out. Hence, a very important part of the data acquisition system is the **trigger**. Its role is to identify interesting interactions - usually called "events" - and, if there is an interesting event, to instruct the computer to read out the data from all the detectors.¹

The **trigger** is usually built by combining the signals from some of the detectors. The trigger might, for example, require signals from two or more scintillators along the beam path in **coincidence** to indicate that a particle passed through the full setup. For example, in the setup shown in Figure 1, the two scintillators - (1.) at the beginning of the beam path through the setup and (5.) at the end - are used as a trigger. When a trigger occurs, data from all detectors is read out and sent to mass storage,

¹The trigger is a fundamental and very complex component of LHC experiments, where interaction rates are very high and only a very small fraction of the interactions are of interest. For example, a Higgs **boson** is only produced in one out of a trillion interactions (where one trillion is 10^{12}).



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usually a hard disk. This mechanism is very similar to when you take a picture with a digital camera. When the shutter-release button is pressed (=trigger), photons hit the sensitive area of the camera (=detector); the photons are ultimately transformed into a digital signal (=data), and this data is stored on the mass storage. One difference is that in the case of BL4S, the exposure time is only about 100 ns.

We do not expect you to design the data acquisition system to trigger and read out the detectors of your experiment. BL4S will provide a data acquisition system for the winning experiments.² For example, at CERN, this system is fast enough to trace typically 3000 particles per second. Please keep this limit in mind and do not propose experiments that study extremely rare effects!

Data Analysis

For answering your research question, you will need to **analyse the data** collected with the different detectors in your experiment. Dedicated software has been developed at CERN, DESY, and elsewhere to analyse experimental data. The analysis software typically used in BL4S is based on a framework called **ROOT**; see Figure 2. ROOT is used by many physics laboratories all over the world. However, you don't need to get familiar with the data analysis tools when preparing your proposal. BL4S will provide the winning teams with the software needed to analyse the collected data, as well as some code and assistance with the data analysis.

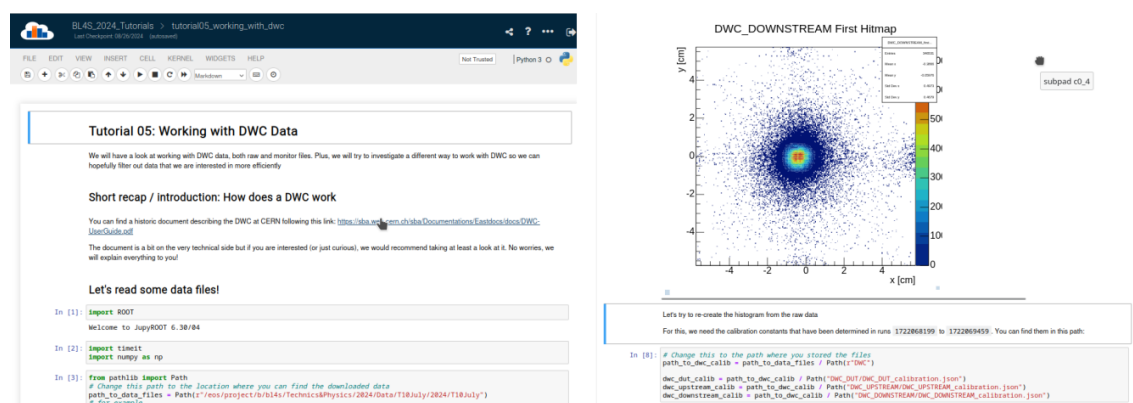


Figure 2: Screenshot of a typical Jupyter notebook using the Python interface to perform data analysis with ROOT.

²The data acquisition system also provides tools for the online monitoring of the experiments in the form of histograms.



Beamlines

In particle physics, the term "**beam**" refers to a large number of particles moving in the same direction. These particles can be accelerated to high energies. **Beamlines** are straight sections of a particle accelerator leading the particles to an experimental area. In such experimental areas, **fixed-target experiments** are conducted. Below, we first describe the beam properties at DESY, CERN and ELSA. Then, we describe two important devices used to shape the beam, namely bending magnets and collimators.

Beam properties at DESY

The beam used in BL4S at DESY is a pure electron beam or a pure positron beam with energies ranging from 1 to 6 GeV. You can choose the properties of the beam needed for your experiments:

- **Particle type:** electrons or positrons.
- **Particle momentum:** any value between 1 GeV/c and 6 GeV/c.
- **Momentum spread:** typically, the momentum spread is around 0.15 GeV/c.

Beam composition and intensity

The number of particles making up the beam depends on the secondary target used when creating the beam (see [Beam production \(optional reading\)](#)), the selected momentum and the type of particle. For example, figure 3 shows the typical **rates** (i.e. the number of particles per unit of time) of electrons available in the experimental area at DESY, depending on the different particle momenta for different secondary targets. Please note that the particles are moving at almost the speed of light and are, hence, relativistic. The beamline at DESY usually provides **one particle at a time**. The particles arrive continuously within an 80-ms cycle, depending on the chosen energy. At high energy, one receives particles, for example, for 20 ms and then not for 60 ms, and so on; while at low energy one receives particles, for example, for 50 ms and then not for 30 ms, and so on. In sum, the **rate is much lower at high energy** than at low energy. Please note that experiments that require a large number of particles (i.e. for irradiation of materials, for collecting enough data for statistical purposes, to search for rarely occurring phenomena, etc.) are better suited for CERN since the overall number of particles can be much higher there.

The beam has a round cross-section. The diameter of the beam is **2 cm** when entering the experimental area. Similar to what happens with light, the further away the beam is from the entrance window, the more it spreads, that is, the diameter becomes wider.

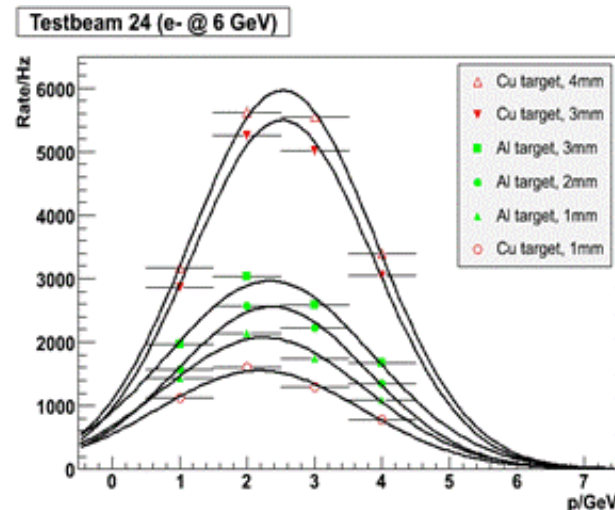


Figure 3: Typical **rate of the single electron beam in the experimental area at DESY** depending on the particle momentum. Rates are shown for different types and thicknesses of the secondary target.

The experimental area at DESY

The BL4S experiments at DESY take place in the **DESY II Test Beam Facility**. The experimental area has a size of about $5 \text{ m} \times 10 \text{ m}$. In this experimental area, the detectors and other equipment can be placed according to the needs of your experiment. In the experimental area, there are some fixed installations, such as a big red magnet (see [The big red dipole magnet at DESY](#)).

Beam production (optional reading)

The particle accelerator is called DESY II, and it is a [Synchrotron](#) accelerating electrons up to an energy of 6.3 GeV. Figure 4 shows how the beam is generated at the DESY II Test Beam Facility.

Inside the DESY II accelerator, [Bremsstrahlung](#) photons are produced by putting a target, called the primary target, into the electron beam. The primary target consists of a $7 \text{ }\mu\text{m}$ thick carbon fibre. When the electrons move through the target, they lose some of their kinetic energy. This energy is transformed into photons, respecting the law of energy conservation. The photons move towards another target, called the secondary target. The secondary target is made of a few mm-thick metal plates. When the photons move through the target, their energy is transformed into pairs of electrons and positrons, again respecting the law of energy conservation. The electron/positron pairs then pass a dipole magnet followed by a collimator (see [Bending magnets](#) and

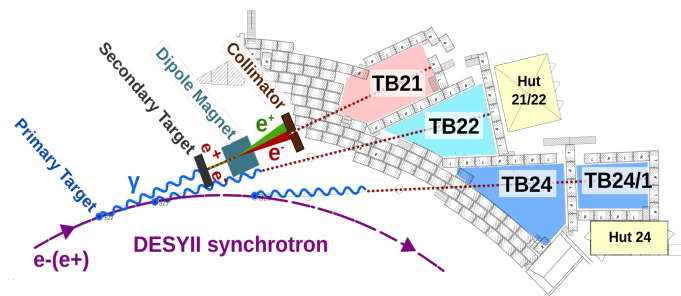
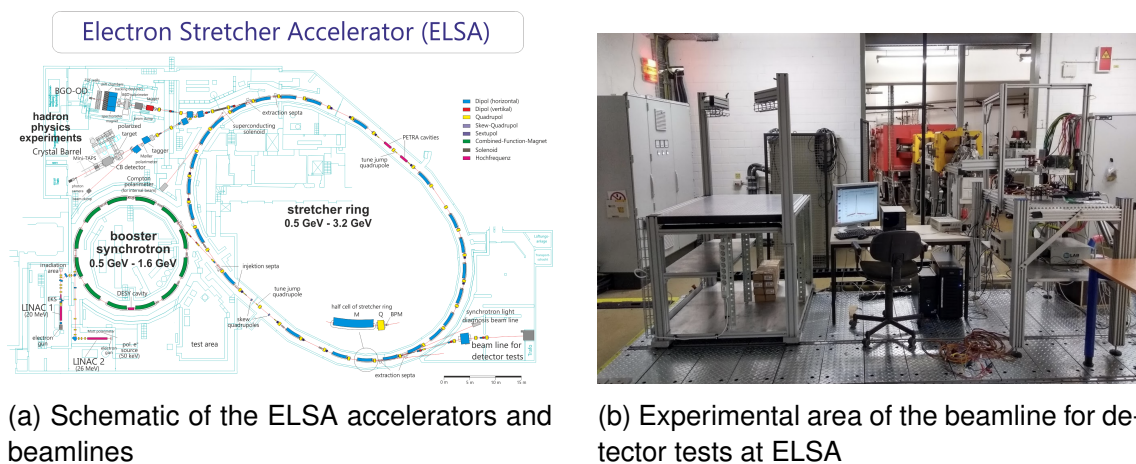


Figure 4: Sketch of the beam production at DESY II.

Collimators). By changing the field strength of a dipole magnet and the opening of the collimator placed after the magnet, one can choose the properties of the beam in the test beam area: One can either have a pure electron beam or a pure positron beam with momenta ranging from 1 to 6 GeV/c. It is **not** possible to have a beam of photons.

Beam properties at ELSA (The University of Bonn)



(a) Schematic of the ELSA accelerators and beamlines

(b) Experimental area of the beamline for detector tests at ELSA

Figure 5: The ELSA layout and a photograph of the experimental area.

The electron accelerator ELSA is operated by the University of Bonn in Germany. It consists of three stages (injector LINACs, booster synchrotron and stretcher ring; see Figure 5a) and delivers a beam of electrons with variable energy of max. 3.5 GeV. The main research topic is hadron physics. Additionally, a dedicated beamline is available for testing detectors in high-energy physics.



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We are using the beamline for detectors for the BL4S projects as shown in Figure 5b. We can provide a monochromatic electron beam with a varying energy between 0.8 and 3.2 GeV. The extraction rate is user-controllable, continuously variable between 1 Hz and 625 MHz and the spill times vary from 3 s to 60 s with a 2 s pause between spills. Possible energy, width and rate combinations of the electron beam at the ELSA are listed in Figure 6.

	energy E	$\frac{\Delta E}{E}$	width/mm	divergence/mrad	rate	current
Min	0.8 GeV	$< 0.2\text{‰}$	$\sigma_x = 1.3$ $\sigma_z = 1.0$	$\sigma'_x = 0.13$ $\sigma'_z = 0.01$	1 Hz	$\approx 0\text{ A}$
Max	3.2 GeV	$< 0.8\text{‰}$	$\sigma_x = 9.0$ $\sigma_z = 6.0$	$\sigma'_x = 2.5$ $\sigma'_z = 3.0$	625 MHz	100 pA

each independently adjustable

Figure 6: Beam properties and possible combinations at ELSA

Beam conditions

We support two types of beamtime, one as a secondary user, one as an exclusive primary user:

1. Simultaneous operation in combination with hadron physics experiments (highly preferred mode!, cost-efficient!)
 - Secondary user
 - Energy fixed to either 2.9 GeV or 3.2 GeV (depending on the running primary experiment)
 - Extraction rate is user-controllable, but limited to 1 Hz up to 100 kHz
 - Spill time fixed to 4 to 8 seconds (depending on running primary experiment)
2. Exclusive operation for the detector test beamline
 - Primary, exclusive user
 - Energy user controllable between 0.8 GeV and 3.2 GeV (change in energy takes roughly 1 to 3 h for beam setup)
 - Extraction rate user-controllable, 1 Hz up to 625 MHz



- Spill time variable from 3 up to 60 seconds

Notes: When needed, a high radiation dose can also be provided to the beam line

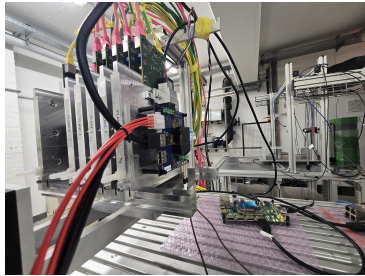
- High dose mode: We can provide 250 ns, up to 2 nC electron pulses for high dose rate studies, corresponding to 40 MGy/s or up to 8 mA. These pulses can be delivered at an energy from 0.8 up to 2.9 GeV and only every 10 to 20 seconds (depending on charge).

Beam diagnostics at the accelerator:

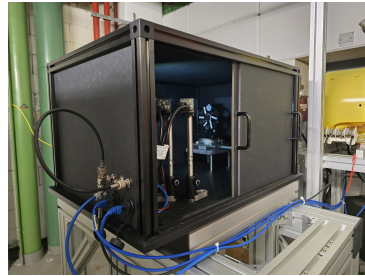
- Chromox screens for beam position and size measurement for high rates (100pA) or in high-dose mode
- Scintillator for rate measurement and control (-> feedback to accelerator), signal also available for users

Detectors

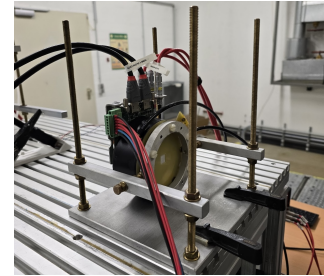
- We can supply scintillators with varying sizes from 1.5 cm x 1.5 cm to 20 cm x 20 cm.
- We can provide a beam telescope with 6x Mimosas26 sensors (ANEMONE telescope) specs: 18.4 μm pitch (tracking resolution of a few μm), 115 μs rolling shutter readout, binary charge info, 2x1 cm^2 active area (see Figure 7a)
- We can provide a "time reference plane" (ATLAS FE-I4) (50x250 μm pixels, 25 ns timestamping, 2x2 cm^2 active area)
- We can provide an AIDA TLU as a trigger system or an EUDET TLU (old version of TLU)
- We have a monochromatic (Daheng Imaging MER2-507-23GM-P) and a colored (Daheng Imaging MER2-507-23GC-P) CMOS camera with a light-tight black box (see Figure 7b)
- We can provide a GridPix-based Time Projection Chamber (TPC) with 3 cm drift length and a 1.5 cm $\times$ 1.5 cm readout area (see Figure 7c). Spatial resolution of 50 μm . The energy sensitivity depends on the chosen gas mixture, and sensitive to electrons, soft X-rays, and charged particles can be detected.
- To be used with the TPC, we can provide a gas mixing unit for precise ratio control and a vacuum pump for lower pressures. Common gases such as Ar and He mixtures with CO₂ are readily available, while the other gases can be procured upon request for specific applications.



(a) Beam telescope



(b) CMOS cameras



(c) TPC

Figure 7: Detector systems used in the BL4S experiment at ELSA: the beam telescope, CMOS cameras in a black box, and a time projection chamber (TPC) with GridPix/Timepix readout.

Magnets

We are not able to provide a magnet.

TDAQ system

We can provide a NIM crate with many modules for setting trigger logic.

We use "pymosa" for DAQ of the beam telescope (<https://github.com/SiLab-Bonn/pymosa>).

We use pybar for DAQ of the time reference (<https://github.com/SiLab-Bonn/pyBAR>).

We use the ELSA control system and scripts to run and take data with the cameras.

We use the Scalable Readout System of RD51 for the DAQ of the TPC (adaptors and FECs). However, taking data using combinations of the beam telescope, cameras and TPC is challenging, so experiments requiring the use of many are not desired.

Beam properties at CERN

The beam at CERN will be provided by the [CLEAR accelerator](#). It is a pure electron beam. The beam's **momentum ranges from 60 to 220 MeV/c**.

Beam composition and intensity

The beam is characterised by the **flux**, that is, the number of particles per unit of time and area.

The beam of the CLEAR accelerator consists of bunches that are grouped in pulses.

A bunch can, in principle, contain a single electron, but we are not able to measure these low intensities. Our intensity monitors work well for charges of 0.01 - 1.5 nC.



Let's see what that means:

How many electrons are in a charge of 0.01 nC?

Calculation: The charge of an electron is $e = 1.602176634 \times 10^{-19} \text{ C}$. $0.01 \text{ nC} = 0.01 \times 10^{-9} \text{ C} = 1 \times 10^{-11} \text{ C}$ Number of electrons: $N = Q / e = (1 \times 10^{-11}) / (1.602176634 \times 10^{-19}) = 6.24 \times 10^7$ electrons

The length of a bunch varies between 0.1 and 1.2 mm. So, a bunch is a "cloud" of millions of electrons that are squeezed together into a small space. All of the electrons in the bunch will hit your target and detectors more or less at the same time. This makes it virtually impossible to study the effects of individual electrons.

The bunches that are provided by CLEAR are grouped into pulses. A pulse can contain between one and 150 bunches, and there can be up to 10 pulses per second. Let's do another calculation to get the maximum beam intensity:

Maximum pulse charge: 87 nC Maximum number of pulses per second: 10
 $Q_{\text{max}} = 87 \text{ nC}$, $f = 10 \text{ Hz}$, $N = \frac{Q \cdot f}{e} = \frac{87 \times 10^{-9} \times 10}{1.602176634 \times 10^{-19}} \approx 5.43 \times 10^{12}$ electrons
So, your target will be hit by more than 5000 billion electrons per second.

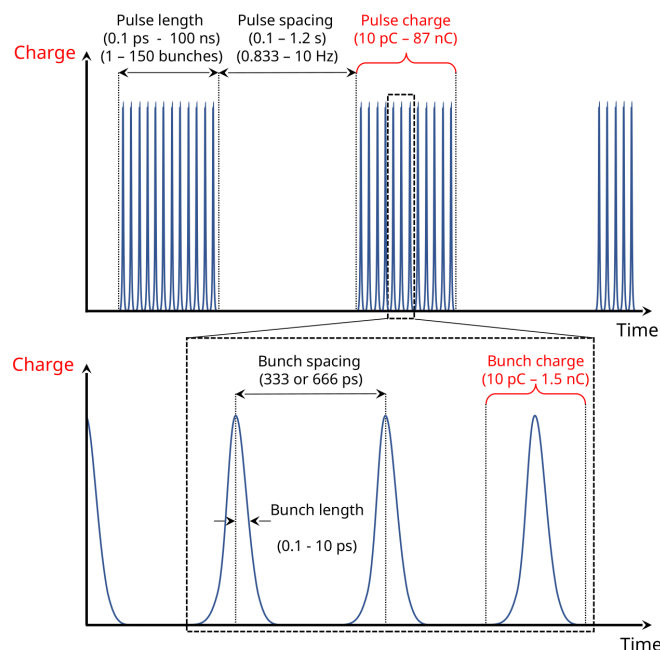


Figure 8: The CLEAR bunch and pulse structure.

The overall number of particles provided by CLEAR can be much higher than what can be achieved at DESY or ELSA. Therefore, experiments that require a large number of particles (e.g. for irradiation of materials) are, in principle, better suited for CERN.



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The beam has a round cross-section. When focused, the beam spot has a diameter of about 1.0 mm close to the exit window (minimum).

The experimental area at CERN

The BL4S experiments at CERN take place at **CLEAR**. The experimental area has a size of about $1\text{ m} \times 1\text{ m}$, and the equipment can be placed according to your experiment's needs (see Figure 9).

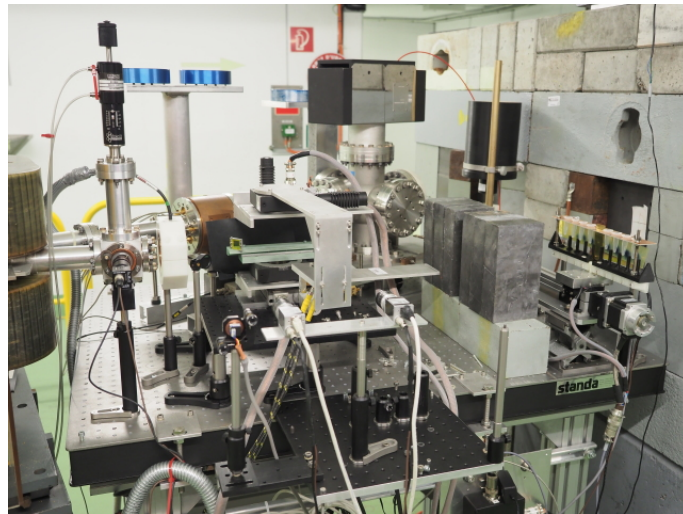


Figure 9: The experimental area at CERN with the experimental setup of some professional scientists.

In addition to the equipment provided by BL4S, it may be possible to install devices that are brought by your team to the experimental area³. Each request will be reviewed individually and will need to respect health and safety guidelines. Due to the small area that is available at CLEAR, you have to propose an experiment that can be realised on a very small footprint. In addition, please note that the CLEAR facility is a supervised radiation area. Access to the area is possible and not dangerous but limited to a few accesses per day for operational reasons.

Take-home messages about the beam

- The beam at **DESY** is a pure electron or positron beam with momenta ranging from 1 GeV/c to 6 GeV/c.

³Please note that CERN cannot guarantee the installation of all the suggested devices.



- The beam at **CERN** is a pure, high intensity electron beam. The particle momentum ranges between 60 MeV/c and 220 MeV/c.
- The beam at **ELSA** is a pure electron beam. Secondary user: Fixed energy of 2.9 or 3.2 GeV, depending on the primary experiment. Primary, exclusive user: Adjustable energy between 0.8 and 3.2 GeV. Changing the energy takes approximately 1 to 3 hours for beam setup.
- At these momenta, the particles are **relativistic**. As an example, the rest mass of an electron is $511 \text{ keV}/c^2$ and, with a momentum of 1 GeV/c, it will travel at 99.99987% of the speed of light.
- Both at CERN and DESY, the cross section of the beam at the focal point is **round with a diameter of 2 cm**. At the ELSA accelerator, the physical size of the electron beam cross section is highly adjustable, but it operates natively in the sub-centimetre to millimetre range (see Fig. 6).

Bending magnets

Bending magnets⁴ are used in beamlines to **change the direction of movement of electrically charged particles**. Moreover, the particles' momenta can be selected by changing the strength of the magnetic field. Hence, bending magnets are typically electromagnets. The strength of the magnetic field can be changed by changing the current intensity. These magnets are dipoles (Figure 10) and the magnetic field is oriented vertically. The particles passing through the magnet will be deflected horizontally, according to the Lorentz force.

The big red dipole magnet at DESY

At DESY, a large dipole magnet is a fixed installation in the experimental area where the BL4S experiments usually take place. It is a dipole electromagnet and is called the "big red magnet". It provides a magnetic field up to 1.35 T (see Figure 11). It has an integrated length (i.e. depth) of about 1 m and an opening that is about 1.5 m wide and 0.35 m high.

Magnets at CERN

Due to the very small size of the experimental area at the CLEAR facility, the installation of a magnet is not possible.

⁴You might consider watching this fantastic [video](#), which provides a great introduction to the electromagnetic field and shows how charged particles move when influenced by a magnetic field (Lorentz force: from 14:51 to 20:58).

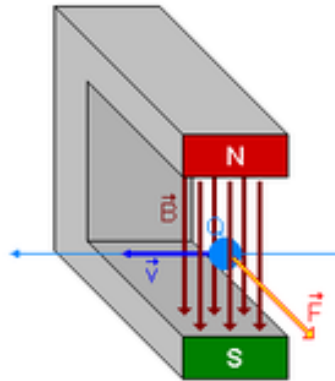


Figure 10: A dipole magnet with a vertical magnetic field and a charged particle moving horizontally through the field. The force is perpendicular to the direction of the magnetic field and the direction of movement of the charged particle, deflecting the charged particle horizontally. Image source: [Wikipedia](#).

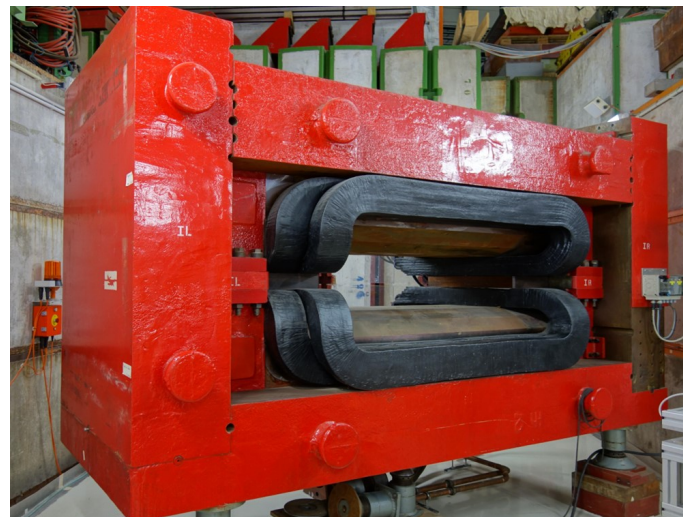


Figure 11: Big Red Magnet, 1.35 T dipole electromagnet

Collimators

Collimators are used to filter the beam. Typically, collimators are used to define the [momentum acceptance](#), the [beam divergence](#), or to reduce the [beam halo](#). The flux available (i.e. the number of particles that cross a defined area in a specific time interval) depends on the collimator settings. The smaller the opening of the collimator,



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the lower the flux of the beam. Don't worry too much about the details of these collimators. The BL4S support scientists will set them up for you.



The BL4S detectors

Look at the detectors as if they were LEGO blocks that can be arranged in different ways to do different things. It is important to understand their properties and limitations. Below is a table that tells you which detectors are available at which institute. Keep in mind that you can also build your own detectors and test them with our beam facilities.

Availability of detectors

Type of Detector	CERN	DESY	Bonn
Scintillators	yes	yes	yes
Electromagnetic calorimeter	no	yes	yes
Beam Telescope	no	yes	yes
TimePix3	yes	—	—
Radiochromic film	yes	no	no
YAG screen and camera	yes	no	no

Table 1: Detector availability

Basic principles of particle detection

For a particle to be detected, it needs to create an electrical signal. To do this, the particle must interact with the material of the detector by transferring energy to it. The electrical signal is usually induced by moving electrons. Therefore, the original particle (whether it is electrically neutral or charged) must go through a process of transformation until electrons are freed that then move through the detector material (see Figure 12).

If the original particle is neutral, it must first cause the production of electrically charged particles. There are several processes by which this can happen, for example, pair-production or strong interactions with nuclei of the material. Once there is an electrically charged particle (either original or from a neutral particle), there are two main ways in which it can interact with the detector material: (1) by directly freeing electrons from the material or (2) by first creating photons that subsequently free

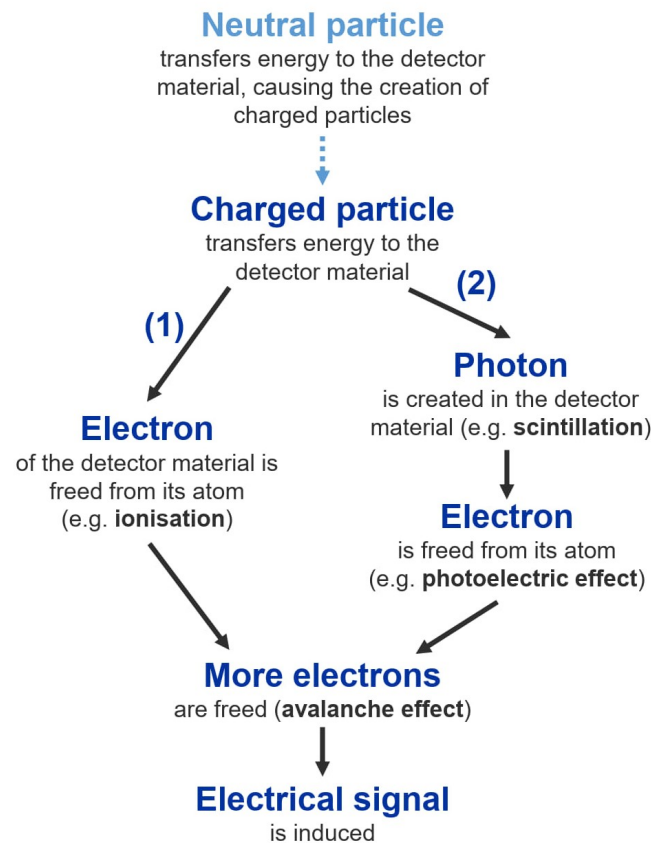


Figure 12: Illustration of the two main ways in which a particle can be detected. Image source: [Physics Education Article](#)

electrons. In both instances, the electron needs to free even more electrons to induce a measurable electrical signal. Below, we will explain the two ways in more detail.

(1) The electrically charged particle directly frees electrons (e.g. ionisation): An electrically charged particle transfers some of its kinetic energy to the material of a gas detector or a semiconductor detector. In a gas detector, an electron of the gas gains the transferred energy and is, thus, freed from its atom, leaving an ion. This process is known as ionisation. The process is similar in semiconducting detector materials, where so-called electron–hole pairs are created, with the main difference being that an electron needs to gain less energy to be freed in a semiconductor than in a gas detector.

(2) The electrically charged particle creates photons (e.g. scintillation or Cherenkov) that subsequently free electrons (e.g. photoelectric effect): An elec-

trically charged particle transfers some of its kinetic energy to a detector, creating a photon (e.g. scintillation or Cherenkov). At the end of the detector, the created photon hits a metallic surface and is absorbed by an electron, causing this electron to be freed. This is known as the photoelectric effect.

Whether the electron is freed (1) directly by the electrically charged particle, or (2) indirectly via a photon, **many more electrons must be freed to finally induce a measurable electrical signal**. By applying a very strong electric field, the initial electron gains sufficient kinetic energy to free more electrons, which can in turn be accelerated and free even more electrons. This process is called the **avalanche effect**, and it results in an amplification of the number of free electrons. As the electrons travel towards the anode, **electrostatic induction** occurs. This is the **electrical signal** that we read out.

BL4S detectors of type (1)

Beam telescopes

A beam telescope can measure the 3D (three-dimensional) track of a particle. Knowing the track of a particle allows pointing to the source of the beam, and thus, the beam telescope is historically called "telescope", like the telescopes used in astronomy. A beam telescope consists of at least three detector planes, which are subsequently ordered along the beam axis. That is, beam telescopes can tell **where a particle passes through the planes of the detector**. A telescope with six planes is visible in Figure 13.

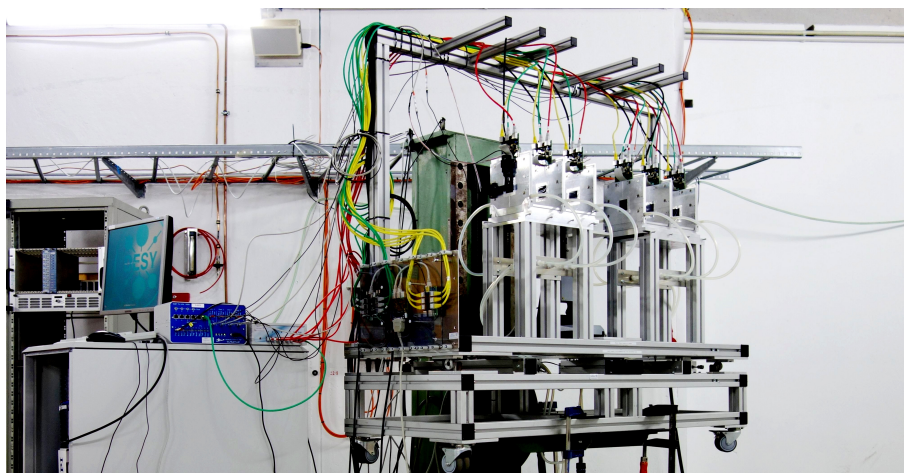


Figure 13: Beam telescope with six planes.



Each plane consists of a 2D (two-dimensional) silicon pixel detector, similar to nowadays mobile phone cameras. Each silicon pixel detector can give the x- and y-coordinates of the position of a particle that passes through. Combining the positions from the different detectors, the 3D track of the particle can be reconstructed. The resolution achievable by a telescope is usually in the order of a few μm . Compared to DWCs, telescopes have by far higher spatial resolution and provide more accurate tracking. However, each 2D silicon pixel detector of the telescope's planes only has an area of $2\text{ cm} \times 2\text{ cm}$.

A typical setup using beam telescopes has three planes before and three planes after a sample under test. With such a setup, one can conduct, for example, scattering experiments to learn more about the internal structure of a material. When the particles (i.e. the beam) interact with the material under test, they will scatter (i.e. move in different directions). Due to the high precision of the telescope's silicon pixel detectors, the scattering angles can be determined.

Further details (optional reading):

Silicon detectors are based on the creation of electron-hole pairs. If a high-energy particle passes through the silicon pixel detector, it will transfer some of its energy to the pixels through which it passes, creating electron-hole pairs. Since the silicon is held in an electric field, the electrons and holes move in opposite directions. The electrons may gain enough energy to free another electron (avalanche effect). Ultimately, they induce an electrical signal (see [Basic principles of particle detection](#)).



UNIVERSITÄT BONN

BL4S detectors of type (2)

Scintillation detectors

A scintillation detector is a 1D (one-dimensional) particle detector based on scintillation (see [Basic principles of particle detection](#)). Scintillation detectors can give information on **whether a particle passed through the plane of the detector**. There are several scintillation detectors with different sensitive areas available for your experiments, from 1 cm × 1 cm to 10 cm × 20 cm. In addition, scintillation detectors can provide time information; that is, they can tell **when a particle passes through the plane of the detector**. Thus, one exemplary use-case of scintillation detectors is [Time-of-flight measurements](#). Knowing the time it took the particle to move from the first scintillation detector to the second scintillation detector, as well as the distance between the detectors, one can also calculate the speed of the particle. The distance between two scintillation detectors can be measured to an accuracy of 1 cm and the time to an accuracy of 1-2 ns.

Another exemplary use case of scintillation detectors is detecting the beam's halo (i.e. particles that move at some distance from the other particles in the centre of the beam).

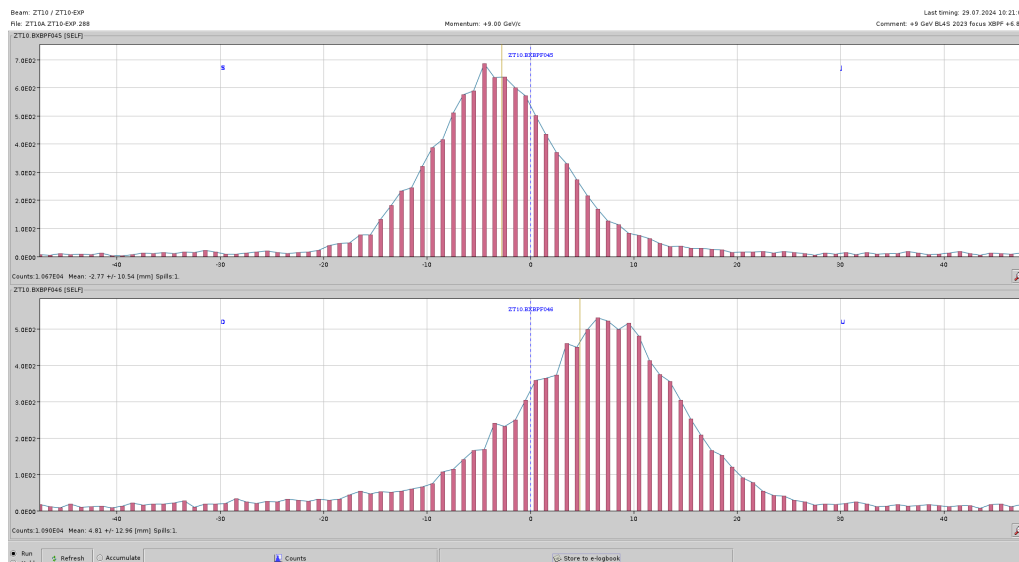


Figure 14: **Distribution of particles forming the beam.** The x-axis shows the position relative to the centre of the experimental area in mm. The y-axis shows the number of particles counted at this position. The upper plot shows the horizontal, and the lower plot the vertical particle count. In the bottom left corner of each plot is the total count of particles (10.7k for horizontal, 10.9k for vertical).

To better understand how the particles are typically distributed, you can have a look at Figure 14, which shows the distribution of the particles. One can see that there are quite a few particles at some distance from the other particles in the centre of the beam. These are the particles that form its halo. To detect the beam's halo, one can arrange, for example, four scintillators around the beam such that they form a hole for the centre of the beam to pass through (Figure 15). One can also use one scintillator with a hole. The opening of the halo detector can range from 1 cm to 15 cm. By detecting the particles of the beam's halo, one can decide not to further consider them for analysis or to flag them (i.e. to mark them as interesting for certain phenomena). For example, it is useful to flag particles that interacted with a material and hence, [scattered](#).

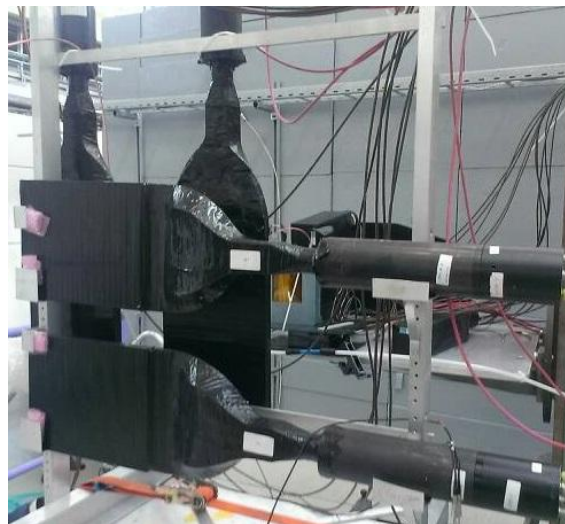


Figure 15: Arrangement of 4 scintillation detectors to detect the beam's halo.

Finally, scintillation detectors can be used to count particles. Moreover, two scintillation detectors measuring in coincidence can form the trigger, making sure that only particles that move through the full setup are considered.

Further details (optional reading):

When an electrically charged particle moves through a scintillation detector, it transfers some of its kinetic energy to the detector. An electron of the detector material absorbs some of the transferred energy and is, thus, at a higher energy level (i.e. the electron is in an “excited state”). The electron returns to its normal energy level (“ground state”) by releasing the transferred energy in the form of a photon. This process is known as **scintillation**.⁵ A scintillation detector consists of a scintillator

⁵Scintillation is an example of luminescence. You can learn more about the different types of luminescence [here](#).



(i.e. a material that exhibits scintillation) and a device that converts the photons into an electric signal. This device can be a photomultiplier tube (which is usually the case for BL4S) or a silicon photomultiplier. A photomultiplier tube consists of a series of electrodes providing electric fields. When entering the photomultiplier tube, the photons emitted by the scintillator hit an electrode. The photon's energy is absorbed by an atom of the electrode, and hence, an electron is freed from the electrode. This process is known as the photoelectric effect. The freed electron gains kinetic energy (i.e. they become faster) because of the electric field provided by the electrodes. An electron can gain enough kinetic energy to free another electron when it hits the next electrode and so on. This process is called the avalanche effect and results in an amplification of the induced electrical signal.

Lead glass calorimeter

A lead glass calorimeter is a 1D (one-dimensional) particle detector based on the Cherenkov effect (see [Basic principles of particle detection](#) and "further details" of the Threshold Cherenkov detector above). A lead glass calorimeter can give information on whether a particle passed through the detector. In addition, it can provide information on the **energy of electrons, positrons, and photons** that pass through it. This is why they are called electromagnetic [calorimeters](#). An electron, positron or photon hitting the calorimeter will produce a fully contained [electromagnetic shower](#). During an electromagnetic shower, all the energy of the incoming particle is transformed into other particles via different processes; for example, Cherenkov photons are created. By measuring the energy of the created particles, the energy of the initial, incoming particle can be measured. 16 lead glass calorimeters are available for the experiment; each has a volume of $10\text{ cm} \times 10\text{ cm} \times 37\text{ cm}$ (Figure 16).



Figure 16: Stack of lead crystal calorimeters.

The energy resolution, σ_E , of the calorimeter is estimated, at energy E , as:

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

Further details (optional reading):

In the electromagnetic shower, all the energy of the incoming particle is transformed into other particles via different processes⁶. For example, some Scintillation photons are created, but many more Cherenkov photons. A lead glass calorimeter consists of a piece of lead glass (i.e. a material that emits Cherenkov photons among others) and of a device that converts the photons into an electric signal. This device can be a photomultiplier tube (which is usually the case for BL4S) or a silicon photomultiplier. The photomultiplier tube attached to the lead glass is specifically tuned to detect Cherenkov photons. A photomultiplier tube consists of a series of electrodes providing electric fields. When entering the photomultiplier tube, the photons emitted by the lead glass hit an electrode. The photon's energy is absorbed by an atom of the electrode, and hence, an electron is freed from the electrode. This process is known as the photoelectric effect. The freed electron gains kinetic energy (i.e. they become faster) because of the electric field provided by the electrodes. An electron can gain enough kinetic energy to free another electron when it hits the next electrode, and so on. This process is called the avalanche effect and results in an amplification of the

⁶For example, via pair-production or strong interactions with nuclei of the material



induced electrical signal.

YAG screen and camera

A YAG screen (Yttrium Aluminium Garnet, often doped with Cerium (Ce)) is a type of scintillating screen commonly used in beam diagnostics for particle accelerators and other high-energy physics experiments.

When a charged particle beam (e.g. electrons) interacts with the YAG crystal, it excites the dopant atoms (typically cerium). The excited electrons in the dopant atoms quickly decay, emitting visible light (usually in the green or yellow spectrum, 520–550 nm for Ce:YAG). This light can be captured by a camera (e.g. CCD or sCMOS).

Specialists at CERN shoot beams at YAG screens and observe the light they produce with such cameras. The intensity and shape of the light spot on the screen provide information about the properties of the beam. It is also possible to install a target in front of the screen that will absorb some of the particles. The camera image will then show the "shadow" that the target casts on the screen.

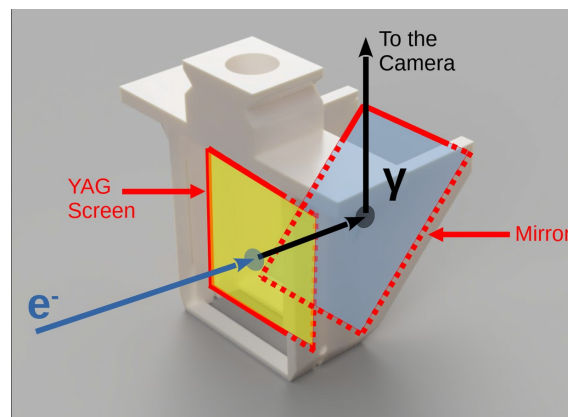


Figure 17: YAG screen



Glossary

Beam divergence

The particles of the beam will spread out while moving along their path. Thus, the diameter of the beam becomes bigger and bigger. [18](#)

Beam halo

Some particles move at some distance to the other particles that form the center of the beam. These particles are called "beam halo". [18](#)

Boson and fermion

Particles can be categorized as bosons or fermions according to their intrinsic spin. Bosons have integer spin numbers, and fermions fractional spin numbers. For example, photons are bosons and electrons are fermions. [7](#)

Bremsstrahlung

A photon produced when a charged particle is deflected by another charged particle. The deflected charged particle loses energy by emitting a bremsstrahlung photon. See also: [Wikipedia: Bremsstrahlung](#). [10](#)

Calorimeter

A detector that measures the energy of a particle. [6](#), [26](#)

Coincidence module

A digital electronic module (essentially a logic "and") that provides an output signal when all input signals are active at the same time. [6](#), [7](#)

**Electromagnetic shower**

An avalanche of particles created when a high-energy particle interacts with the material of a calorimeter. This process is called "shower" because the particles are produced both from the interaction of the initial particles with the material and from further interactions of the newly produced particles and so on. In an electromagnetic shower, incoming electrons, positrons or photons cause the creation of new bremsstrahlung photons and electron/positron-pairs. [26](#)

GeV

Electronvolt (eV) is a unit of energy used in particle physics. One electronvolt is defined as the energy gained by one electron accelerated by a potential difference of 1 V: $1 \text{ GeV} = 1.6 \times 10^{-10} \text{ Joule}$. The letter G stands for Giga, $1 \text{ GeV} = 1 \times 10^9 \text{ eV}$. [5](#)

GeV/c

A unit of momentum used in particle physics. [5](#)

GeV/c²

A unit of mass used in particle physics. $1 \text{ GeV}/c^2 = 1.783 \times 10^{-27} \text{ kg}$, where c is the speed of light. [5](#)

Momentum

Product of 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: $\mathbf{p} = m \cdot \gamma \cdot \mathbf{v}$, 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. [5](#)

Momentum acceptance

The range of particle momenta that will be accepted and registered by a detector. For example, one could set a minimum momentum value, and hence, only particles with a momentum above this minimum value will be considered. [18](#)



Root	A software to display and analyse physics data. We use it a lot in BL4S. 8
Scattering	Scattering means that an incoming particle interacts with another particle in such a way that the incoming particle changes its direction of movement. There are several different types of scattering. For example, inelastic scattering can lead to the creation of new particles. 25
Scintillation detector	A scintillation detector consists of a scintillator (i.e. a material that exhibits scintillation) and a photomultiplier (i.e. a device that converts the photons emitted by the scintillator into electrical signals). The size of the electrical signal is proportional to the energy of the initial electrically charged particle. For example, a particle with a really high energy will lead to a really high electric signal. 6
Synchrotron	A specific type of particle accelerator, in which the particles are accelerated and move along a circular path. The field strength of the magnets, which make the particles move along a circular path, is synchronized to the increasing kinetic energy of the particles, that is, it becomes bigger with time during the accelerating process. See also: Wikipedia: Synchrotron . 10
Time-of-flight measurements	Measuring the time a particle takes to move a certain distance. Time-of-flight (ToF) measurements provide information about the speed of the particle, and hence, other characteristics, such as momentum or particle type, can be deduced. 24
Tracking	Measuring the trajectory of a particle. 6



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Trigger

The trigger identifies interesting interactions (“events”) and instructs the computer to collect the data from all the detectors when there is an interesting event. [6](#), [7](#)