Chapter 22
Future Developments of Detectors

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22.1   Introduction

Large scale detectors in particle physics take many years to plan and to build. The last generation of large particle physics detectors for the energy frontier, ATLAS and CMS, have been operating for more than 10 years, and upgrades for them are now being done. Studies for the next generation of experimental facilities have been ongoing for a number of years. In this section future directions in integrated detector design are discussed, as they were visible at the time of writing this report.

At the moment the biggest approved project in particle physics is the upgrade of the Large Hadron Collider (LHC) towards high luminosity running. This project is scheduled to be completed by 2027, and major upgrades to the two main collider detectors ATLAS and CMS are planned. Beyond the LHC, an electron-positron collider has been discussed for many years, to fully explore the Higgs and the top sector and to complement the discovery reach of a hadron machine at the energy frontier with a high precision program.

The requirements as far as detectors are concerned are very different for these two types of projects: for the LHC luminosity upgrade fundamental changes to the underlying philosophy of the existing detectors are not possible, but significant technological development is needed to meet the challenges of extreme radiation environments and high event rates. For a yet not existing electron-positron collider a detector can be designed from ground up, optimised to meet the ambitious physics agenda of such a facility.

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Several strategy discussions at national and international levels have consistently put a high energy electron positron collider far up on the list of future projects in the field [1–4]. Such a facility should serve as a Higgs factory, run at least at an energy of 250 GeV, but should also provide an upgrade path towards the top threshold and beyond. With the results from the current run of the LHC which show no indications of direct signs for new physics, the role of ultimate precision especially at the Higgs production threshold has been much strengthened [5].

The International Linear Collider, ILC, is a mature project to build an electron-positron collider, which could eventually push into the TeV regime, realised as a linear accelerator. The facility is described in the Technical Design Report from 2012 [6], and targets an initial energy of 250 GeV, upgradable to 1 TeV. To reach energies in the multi-TeV range in an electron-positron collider, another technology will be needed. The CLIC technology, developed mostly at CERN, is a promising candidate for such a machine [7, 8].

With the strong emphasis on precision Higgs physics, circular machines have become again a subject of study. A circular collider like the FCC-ee project, pursued at CERN [9], could reach the Higgs and possibly the top pair threshold in a ring of around 100 km circumference. Such a facility could also be used for the next large hadron collider, reaching energies of up to 100 TeV [10]. A similar project, CEPC/SppC, is under discussion in China [11–13].

A number of smaller projects are currently pursued in the field of experimental high-energy physics as well, for example, the B-factory at KEK, or long baseline neutrino experiments like Dune.

22.2   Challenges at Future Colliding Beam Facilities

The Large Hadron Collider, LHC, has seen first beams in 2008. Until 2018, a spectacular physics harvest has taken place, with the undisputed highlight the discovery of the long-sought-after Higgs particle in 2012. The energy of the collider has reached its design value, and the collider will continue to run in this configuration for another approximately 5 years, until 2024.

Already now the LHC has exceeded its design luminosity of $10^{34} \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ and is expected to accumulate a total integrated luminosity of $300\,\mathrm{fb}^{-1}$ in the first running phase ("Phase-I") that extends to 2024. This will result in significant new insights into the physics of the electroweak symmetry breaking, and significant new information on physics beyond the standard model.

During the Phase-II, starting around 2027 and extending to 2035 or beyond, the LHC will increase its luminosity by about a factor of 10. ATLAS and CMS will extend their physics reach [15] significantly with this upgrade. The discovery reach for supersymmetric particles for example will be extended by some 20–30%, access to rare decay modes e.g. of the Higgs Boson will be improved, and flavour changing neutral currents through top decays might become accessible. Many other measurements will profit from this improvement as well. However, the increased

luminosity is payed for with more severe background conditions, with a much larger number of events per beam crossing, and a resulting challenge to the sub-detectors. In particular the innermost detectors will need major upgrades, together with the readout and data acquisition systems, to handle the new conditions.

It should be noted here that also studies have been initiated for detectors of possible future very large hadron colliders that could succeed the LHC and explore energy ranges of up to 100 TeV. One such concept of a hekto-TeV hadron collider is discussed within the framework of the FCC-hh study at CERN [10], another, SPPC, is part of the CEPC study in China [12]. The requirements for the detectors of such machines are just being explored and are far from being fully understood. The main challenges are related to the large jet energies and boosted event topologies, that require very large magnetic fields, large detector dimensions, and highly segmented detectors. In addition, the radiation environment is harsh and requires very radiation hard detectors.

An electron-positron collider like the ILC or FCC-ee poses different but unique challenges to its detectors. It puts a premium on precision physics, particularly on the precision reconstruction of jet masses. The experimental environment is benign by LHC standards, which allows one to consider technologies and solutions which have not been possible during the development of the LHC detectors.

To reach high precision in the overall reconstruction of event properties, each sub-system must reach excellent precision by itself. In addition, however, in the combination of sub-systems into a complete detector extreme care has to be taken to be able to fully utilise the precision of the sub-detectors. Among the most relevant parameters is the amount of dead material, in particular for the inner tracking detectors, and its radiation hardness. Low mass detectors are a key requirement, and add a major challenge to the system. High readout-speed is another ingredient, without which the high luminosity of the collider can not be exploited fully.

An experiment at an electron-positron collider has to be designed to extract maximum information from the event, and utilise the available luminosity as much as possible. It has to be able to reconstruct as many different topologies and final states as possible. This implies that the focus of the development has to be the reconstruction of hadronic final states, which are by far the most numerous ones in nearly all reactions of interest. A typical event topology is a multi-jet final state, with typical jet energies of order of 50–100 GeV. In contrast to the LHC, where many collisions occur in one bunch crossing, typically only one event of interest takes place at the linear collider, even at very high luminosities. With well below 100 particles per jet the total number of particles in the final state is comparatively small. This makes it possible to attempt the reconstruction of every single particle, neutral or charged, in the event. A major focus of the detector development therefore will be the capability of the detector to identify individual particles as efficiently as possible, and to reconstruct the properties of each particle as precisely as possible. This has large implications for the overall design of the detector.

Even though the event topology at an electron-positron collider is intrinsically clean, and there are no underlying events nor multiple interactions, as they are present in a hadron collider, backgrounds nevertheless do play a role. In particular

for the innermost and the most forward systems, beam induced backgrounds are significant. Electron-positron pairs created in the interaction of the two highly charged bunches add significant background to the event, and detectors close to the beam need to be able to cope with these. This background is particularly relevant at linear colliders, which, due to the smaller repetition rate of the interactions, need to focus their beams very strongly at the interaction region to reach the luminosity goals. Circular electron-positron colliders on the other hand can operate with less strongly focussed beams, since they re-use the beams after each turn, operating at much larger repetition rates.

22.3 Hadron Colliders

The LHC and its envisaged upgrade to the HL-LHC provides a physics program well until the middle of the 2030s. As discussed above, plans for the next colliders at the energy frontier are being made already now. A possible far-future option is a very large hadron collider. Recently, the conceptual design report for the Future Circular Collider (FCC), a $\approx$100 km long storage ring proposed for CERN, has been published. The proposal foresees to start with an e^+e^- collider for Higgs precision studies (FCC-ee [9]) that could be replaced by a hadron collider, the FCC-hh [10], at a later stage, probably not before the 2060s. Table 22.1 summarises the basic parameters of HL-LHC and FCC-hh in comparison to the LHC.

The LHC detectors are operating since quite some time now and are very well understood. This experience helped to design the upgrades that are required to cope with the challenges of the oncoming LHC luminosity upgrade, as will be discussed in the next Sect. 22.3.1. The FCC-hh challenges to the detectors are quite different; first concepts for detectors are under discussion and will be presented in Sect. 22.3.2.

Table 22.1 Some basic design parameters of the LHC, HL-LHC and FCC-hh (nominal) [10]

Parameter	Unit	LHC	HL-LHC	FCC-hh
Center-of-mass energy	TeV	14	14	100
Peak luminosity/IP	10^{34} cm^{-2} s^{-1}	1	5	30
Number of bunches	#	2808	2808	10,400
Bunch population	10^{11}	1.15	2.2	1.0
Time between bunches	ns	25	25	25
Beam spot size at IP	μm	16.7	7.1	3.5
Bunch length	cm	7.55	7.55	8
Accelerator length	km	27	27	97.75
Peak pile-up events/bunch crossing	#	25	130	950
Pile-up line density	mm^{-1}	0.2	1.0	8.1
Pile-up time density	ps^{-1}	0.1	0.29	2.43
Total ionising dose at $r = 2.5$ cm	MGy	1.3	13	270

22.3.1 Detector Upgrades for the High-Luminosity-LHC

The two major colliding beam experiments at the LHC, ATLAS and CMS, have recorded large data sets starting in 2010. The currently installed innermost detectors were designed to cope with track densities and to withstand the radiation doses expected during the LHC Phase-I running that extends until 2024. For the high-luminosity operation phase of the LHC both experiments will replace their inner tracking detector with completely new systems.

The tracking detectors of both large LHC experiments are mostly based on silicon technology detectors. Over the past years, an intense R&D effort has taken place, to re-design and re-optimise the inner detectors for both ATLAS and CMS. Fundamentally no changes in technology will take place, both detectors will rely on an all-silicon solution for the tracking. In addition, ATLAS will remove the transition radiation detector from its system, and extend its silicon tracker to larger radii. Owing to the track trigger concept, CMS completely re-designs its tracker and utilises novel detector modules that allow for an on-module p_T discrimination of charged particle tracks. Both Phase-II trackers will again follow a classical barrel and end cap design. However, compared to the Phase-I trackers, ATLAS will use wedge-shaped sensor modules in its end caps of the tracker, whereas CMS will rely on rectangular modules in this part of the detector. Both future trackers will have substantially increased granularity to cope with the expected pile up of up to 200 events per bunch crossing, and very much improved radiation tolerance, which will significantly go beyond the one of the Phase-I detectors and suffice for operation throughout the Phase-II era.

The amount of insensitive material is a significant performance limiting factor of the current trackers, both at ATLAS and at CMS. The large amount of material in the present trackers not only reduces the performance of the trackers themselves, but also has a negative impact on the performance of the electromagnetic calorimeters directly outside of the tracking systems. The reduction of material is therefore another important goal of the tracker upgrades. CMS will use 320 μm thick sensors with an active thickness of 200 μm, as compared to 500 μm thickness in the present detector, novel structural materials, and novel powering and cooling schemes will make this goal achievable.

For the innermost layers of the future trackers radiation tolerance will be of even larger importance than today. Current technologies are not able to withstand the anticipated rates for longer periods. A number of novel technologies are under consideration, 3D Silicon pixel sensors or diamond tracking detectors. Even solutions which do not involve Silicon—like Micromegas trackers—are being discussed.

The higher rates at the upgraded LHC will not only challenge the hardware of the tracker, but also put large demands on the readout and the trigger system. In particular, the latter will have to be significantly upgraded to handle the anticipated rates without a loss of sensitivity. The tracker might well play a central role here, as the early trigger on track-like objects already in the level-1 trigger will significantly

reduce the trigger rate. Triggering on tracks rather than just increasing the trigger thresholds will maintain a much better sensitivity to a broad range of signals, in particular for the much sought-after new physics signals.

The final layout is based on the concept of a "long pixel" detector. In this Ansatz the pixel size is increased compared to current pixels to something like $100\,\mu m \times 2\,mm$. It appears possible to keep the power per pixel constant compared to current pixel readouts, thus resulting in a tracker which has a channel count larger by two orders of magnitude than the current strip trackers, but a similar overall power consumption.

Although the tracking detectors are most affected by the increased luminosity, other detectors will be affected as well. The calorimeters will see much increased backgrounds in the forward direction, which might necessitate upgrades or significant changes. A serious problem might be that the ATLAS liquid argon calorimeter in the forward direction heats up under the backgrounds to a point where is will no longer function. In this case—which will only be known once operational experience under real LHC conditions is available—the replacement by a warm forward calorimeter might be necessary. CMS intends to make major changes to its calorimeter system, replacing the hadronic section and part of the electromagnetic section with a highly granular calorimeter, using technology which has been developed and will be described later in the section on detectors at electron positron colliders. For all detectors the capability to handle larger rates will be needed, and might make updates and replacements of the readout electronics necessary. This even applies to parts of the muon system, again primarily in the forward direction. ATLAS e.g. is considering to replace the drift tubes in the forward direction with ones of smaller diameter, to limit the occupancy. In any case upgrades to the trigger and the data acquisition are needed.

22.3.1.1 Novel Powering Schemes

The minimisation of power consumption will play a central role in the upgrades of the LHC tracker detectors for the LHC Phase-II. Traditionally readout electronics are the main generators of heat in the detectors, which needs to be cooled away. Both ATLAS and CMS employ sophisticated liquid cooling systems, operating at pressures below the atmospheric pressure, to cool away approximately 33 kW from the tracking detector alone. Power is brought to the electronics at low voltages, typical for semiconductor operation. The resulting large cross sections of conductors add significantly to the overall material of the detector.

Several alternative schemes are under consideration, to limit the material and volume needed by the power lines. In one approach, called DC-DC, a large voltage is provided at the frontend. For the same power delivered a significant reduction of the amount of copper needed can be obtained. On the front-end the larger voltage is then transformed to the needed lower voltage. An optimised method to transform

the voltages without large power loss, and without large and bulky circuitry, is the subject of intense R&D.

An alternative option is serial powering. Here as well power is supplied to the front-end at a high potential. By putting several readout circuits in series, the power is reduced at each chip to the needed level. This approach promises reduced power loss and less material at the detector, but presents the experimenter with problems of proper grounding of the detector elements. By putting systems in series potentially a correlation between chips due to changing power consumption levels may be introduced. This method as well is the subject of intense R&D.

22.3.1.2 Novel Mechanical Structures and Cooling

The all-silicon trackers developed for the ATLAS and CMS operation at LHC Phase-II conditions rely on sophisticated mechanical systems, which are light-weight and at the same time provide the necessary precision and services to the detector modules. They need to be able to operate at low temperatures, and withstand thermal cycles with a temperature differential of up to 50°.

In contrast to previous designs, where cooling and positioning of modules was achieved via separate features of the mechanical structures, the new designs will combine these functionalities in single features with the goal of substantially reducing the amount of passive materials in the tracker volume. In addition, bi-phase evaporative CO_2 cooling will be used as coolant, which not only has a larger radiation length X_0 compared to conventional coolants, but also allows to use pipes with smaller diameters and wall thickness, which even further reduces the material budget. However, smaller pipe diameters require significant improvements in the type of heat spreaders that are used to transport the heat from the source to the coolant. Due to their thermal properties carbon foams are widely used for this purpose. They provide a relatively large thermal conductivity at low mass. Moreover, carbon foams can be tuned to the specific needs of an application, by adjusting the pore-size and the amount of carbon deposited on the cell structure, which defines both the density of the foam and its thermal conductivity. Figure 22.1 shows a microscopic image of a stainless steel cooling pipe embedded in a block of carbon foam. In the sample shown the heat transfer between foam and cooling pipe is established via a layer of Boron Nitride doped glue that is pushed into the open-pore foam.

Support structures for silicon tracking devices are typically made of carbon fibre reinforced polymer (CFRP), which—due the demand of high stiffness rather than high strength—employ high or even ultra-high modulus carbon fibres. These fibres have the positive side effect that carbon fibres with a high Young modulus typically also have a large thermal conductivity in fibre direction, which is beneficial for cooling the detector or is even actively used for cooling. As the HL-LHC trackers are designed for an integrated luminosity of up to $4000\,\text{fb}^{-1}$ over a operation time of 12 years without maintenance and several thermo cycles, longevity and in particular moisture uptake is a concern for the mechanical support systems.
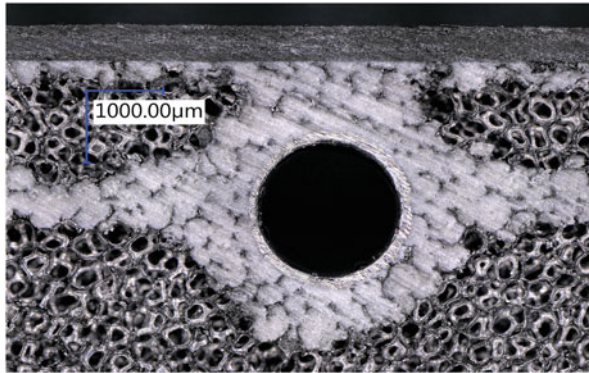
Fig. 22.1 Stainless steel cooling pipe embedded in a block of Carbon foam (credit DESY)

CFRPs with cyanate ester based resin systems are known for their low moisture uptake, however, recent industrial developments show that epoxy based systems have similar behaviour with the advantage of longer shelf life times and thus easier use of the raw material.

In general machining of CFRP with the precision required for e.g. positioning of the sensitive detector modules is not feasible, especially for layouts with small number of layers. The designs of tracker support structure therefore often follow the paradigm of "precision by glueing". The positioning elements requiring high precision machining and placement are made from e.g. Aluminium or PEEK plastic and placed on a jig prior to the assembly. The CFRP parts are then glued to these positioning elements resulting in a stiff and precise support structure. With this design and production method the tolerances on the machining and production of the used CFRP can be relaxed, which eases the production process and reduces cost while maintaining the quality of the final support structure.

22.3.2 Emerging Detector Concepts for the FCC-hh

FCC-hh will pose new challenges to the detectors [10]. A 100 TeV proton collider has not only discovery potential, given by the increased energy compared to LHC, but will also provide precision measurements as the cross sections for Standard Model (SM) processes in combination with the high luminosity lead to large event samples [13]. The envisaged detector concepts must therefore be able to measure multi-TeV jets, leptons, and photons from heavy resonances as well as Standard Model processes with high precision. As the established SM particles are small in mass, compared to the 100 TeV CMS energy of the collider, event topologies will be heavily boosted into the forward directions. A further challenge are the expected simultaneous pp collisions in one bunch crossing ('pile-up') that are expected to

reach numbers of 1000 at the FCC-hh, significantly above what is seen at LHC (60) and expected for HL-LHC (200). In particular, the anticipated separation between vertices of pile-up events is of the same order as the multiple scattering effect on the tracker vertex resolution, which renders resolving pile-up with classical 3D tracking nearly impossible. A promising approach to overcome this problem is to use 4D tracking by adding precise timing information to the tracker hits and exploiting the time structure of the pile-up events. For its HL-LHC operation the CMS experiment is foreseeing this approach already by introducing of the so-called MIP Timing Detector (MTD) that will be installed directly after the future tracker and provide timing information with a resolution of about 30 ps [14].

A reference detector for FCC-hh has been defined that at this time does not represent a specific choice for the final implementation, but rather serves as a concept for the study of physics potential and subsystem studies [10]. Figure 22.2 shows a rendering of the reference detector together with a quadrant view that shows the coverages in $|\eta|$. The detector has an overall length of 50 m and a diameter of 20 m. The central detector covers the regions of $|\eta| \leq 2.5$. Two forward
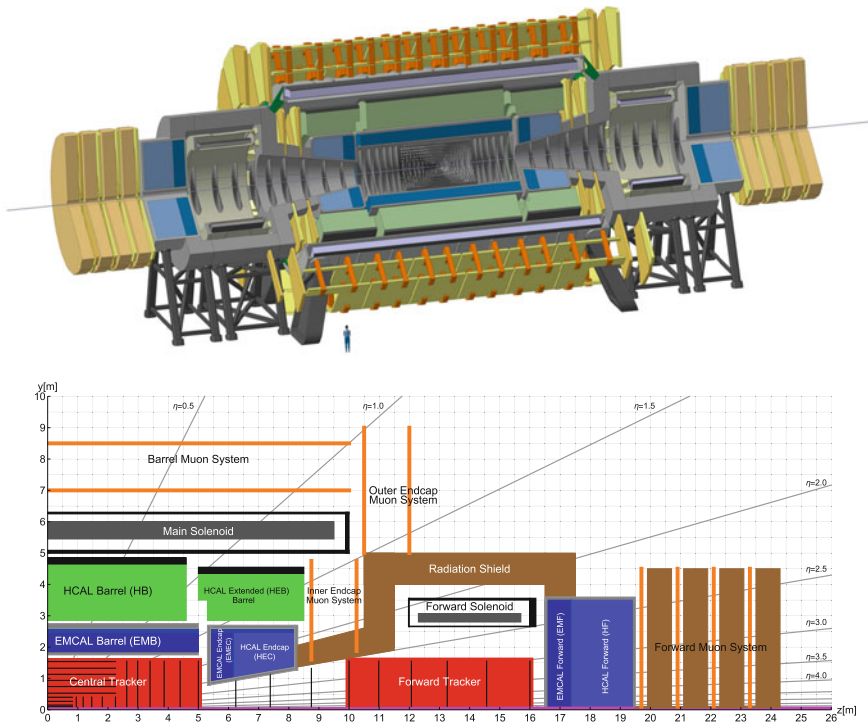

Fig. 22.2 The FCC-hh reference detector (top) has an overall length of 50 m and a diameter of 20 m. The quadrant view (bottom) shows the main detector elements and the coverage in $|\eta|$. Both figures from [10] (credit CERN/CC BY 4.0)

spectrometers cover rapidity regions of up to $|\eta| \approx 4$. A central detector solenoid with an inner bore of 10 m delivers a field of 4 T for the central regions. Two options are under study for the forward spectrometer magnets, either solenoids or dipoles. No iron return yokes are foresee, as the necessary amount of iron would be very heavy and expensive. As a consequence, the magnetic stray fields in the detector cavern will be significant which raises the need for separate service caverns some distance away.

The central tracker extends to a radius of 1.6 m. The calorimeter system consists of a LAr electromagnetic calorimeter with a thickness of 30 radiation lengths and a scintillator-iron based hadronic calorimeter of 10.5 nuclear interaction lengths. A muon system is foreseen for the outer and forward parts of the detector.

A significant challenge for the FCC-hh detector will be the radiation levels. Figure 22.3 (top) shows the expected total ionising dose rate in the detector components after a total luminosity of 30 ab^{-1} has been integrated. It is expected that the total rate for the inner tracking layers would accumulate to about 300 MGy. The radiation levels in the hadronic calorimeters would be at about 6–8 kGy,
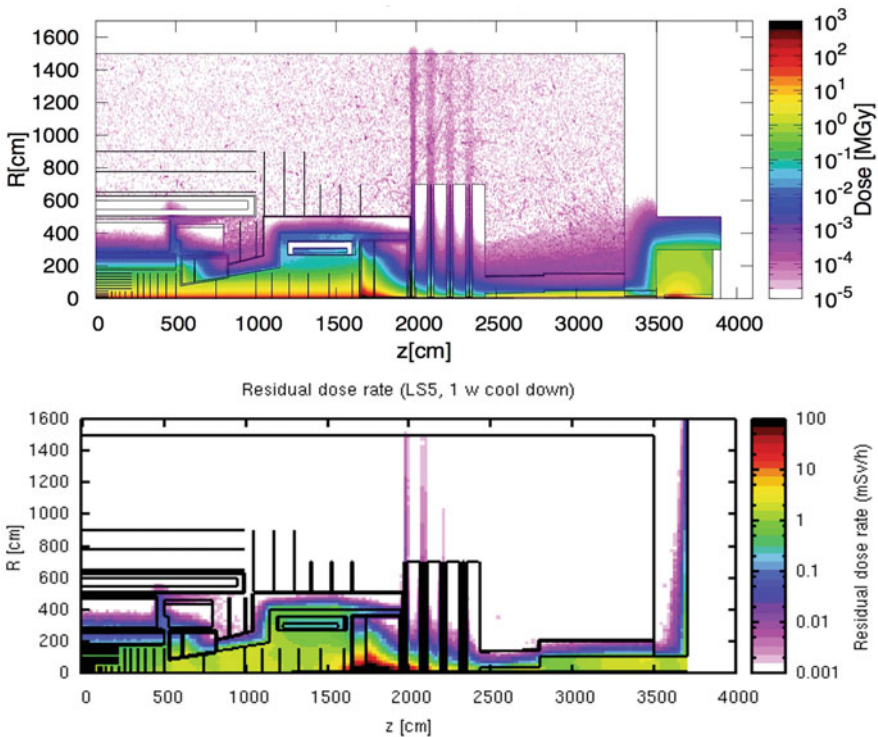

Fig. 22.3 Top: Total ionising dose for 30 ab^{-1} of integrated luminosity. Bottom: Radiation dose after one week of cool-down towards the end of the FCC-hh operation [10] (credit CERN/CC BY 4.0)

which is below the limiting number for the use of organic scintillators. Figure 22.3 (bottom) shows the radiation dose rate after one week of cool-down time towards the end of FCC-hh operations. The resulting dose rates of about 1 mSv/h in the tracker volume put limitations on person access for maintenance purposes.

22.4   Electron-Positron Colliders

The realisation of high energy electron-positron collisions has been the subject of many studies over the last years. Two fundamentally different options exist: a large circular collider, as e.g. proposed in form of the FCC-ee at CERN, or a linear collider. Due to synchroton radiation losses a circular collider is limited in its energy reach. The FCC proposal, with a ring of about 100 km in circumference, could reach with acceptable losses a final energy enough to reach the top-pair production threshold. It is economically not very sensible to go beyond this energy stage.

A linear accelerator on the other hand is intrinsically capable to reach higher energies, by extending the length of the accelerator. Over the last 20 years several technologies have been developed which promise to reach a centre-of-mass energy of 1 TeV. The international linear collider, ILC, uses superconducting cavities, a by now well established and mature technology. A fully costed design has been published in 2012 [16]. With the successful completion of the construction of the European XFEL, a large system based on the same technology has been build and successfully commissioned, providing a solid basis for estimating both costs and risks associated with this technology. An artist's drawing of the ILC facility is shown in Fig. 22.4.

To reach even higher energies the superconducting technology is not very well suited, as the achievable accelerating gradients are limited and, thus, the systems
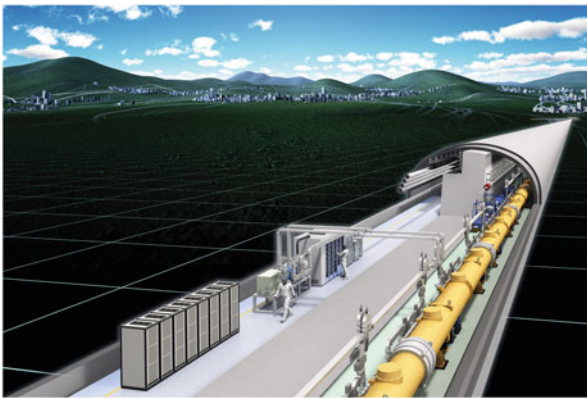

Fig. 22.4 Artist's view of the ILC tunnel in Japan. Credit: Rey Hori/KEK

will become too large. An option based on normal conducting cavities and an innovative two-beam acceleration scheme is under development at CERN in the context of the CLIC collaboration. Even more ambitious projects like plasma accelerators are being discussed as well, but are far from being available for large scale systems [17].

Politically, Japan has been discussing to come forward and host the ILC. At the time of writing this report, no final decision has been reached.

At the core of the ILC are superconducting radio-frequency cavities, made from Niobium, which accelerate the beams. After many years of intense research and development the Tesla Technology Collaboration (TTC, [18]) has developed these cavities and industrialised their production. About 800 such cavities are used in the European Free Electron Laser, built at DESY, the European XFEL [19]. Here an average acceleration gradient of 23.5 MV/m has been reached routinely, with most cavities exceeding the design value by far, almost reaching ILC design requirements. For the ILC a gradient of 31.5 MV/m is anticipated, which, however, at the time of writing this report seems to be in reach, but has not yet been realised for large numbers of cavities nor in an industrial type series production environment. Recently, an intense R&D efforts has been started to further increase the reachable gradients in superconducting RF structures. Nitrogen doping, discovered at Fermilab [20], is one subject of study, as are alternative shapes of the cavities, optimisation of the preparation of the Niobium material, and other ideas. It is hoped that the results from this R&D, which is however not the subject of this review, will significantly reduce the cost of the ILC project.

The ILC facility poses many additional challenges to the accelerator builder, which are being attacked in an intense and long-term research and development (R&D) program. The preparation of low emittance beams, the production of high intensity polarised positron beams, and the final focus of the high energy beams down to nanometer spot sizes are just some of these [21].

The key parameters of the proposed ILC facility are summarised in Table 22.2. With the current knowledge from the LHC, the importance of a high luminosity run at the Higgs threshold is strongly stressed, which led to the re-definition of the first stage of the ILC as a 250 GeV collider [24]. This also results in a significant cost saving for this first stage, an important consideration for the political discussions taking place in Japan and elsewhere. Such a collider could be realised in a tunnel infrastructure of about 20 km length. In Japan a promising site in the north of the country has been identified, which is under close scrutiny at the moment. However, it should be noted that no official decision has been reached by Japan neither on hosting the ILC, nor on its location within Japan.

The CLIC accelerator is based on normal conducting cavities, operated at 12 GHz, reaching gradients of between 80 and 120 MV/m. It is based on a novel 2-beam acceleration scheme, where one high power, low energy beam is used to produce the radio frequency needed to accelerate the high energy beam. The feasibility of this technology is investigated at CERN at the CLIC Test Facility. Over

Table 22.2 Some basic design parameters of the ILC (250 and 500 GeV options [22, 24]), CLIC (3 TeV option) [8] and FCC-ee (240 GeV parameters) [9]

Parameter	Unit	ILC-250	ILC-500	CLIC	FCC-ee
Center-of-mass energy	GeV	250	500	3000	240
Peak luminosity/IP	$cm^{-2}s^{-1}$	1.35×10^{34}	1.79×10^{34}	5.9×10^{34}	8.5×10^{34}
Pulse rate	Hz	5	5	50	
Pulse length	µs	727	727	0.24	
Number of bunches/pulse	#	1312	1312	312	328/beam
Time between bunches	ns	554	554	0.5	994
Beam size (horizontal) at IP	nm	516	474	40	13,748
Beam size (vertical) at IP	nm	7.7	5.9	1	36
Bunch length at IP	µm	300	300	44	3150
Electron polarisation	%	>80	>80	>80	0
Positron polarisation (optional)	%	>30	>30	>30	0
Accelerator length	km	20.5	33.4	$\approx$50	97.756
Total site AC power	MW	129	164	589	308

the last year significant progress was made on demonstrating the CLIC technology (see [8] and references therein). However a major limitation remains the lack of a significant demonstration setup, which would allow full system tests in a sizeable installation.

In recent years efforts to study a circular collider option have intensified. Both at CERN and in China designs are being developed for a circular collider, based in a tunnel of about 100km in circumference, which could host an electron positron collider. The technology for such a collider is available and does not provide unsurmountable challenges, apart from the scale of the project. A design study is currently ongoing, led by CERN, to develop a conceptual design report for a such a collider hosted in the Geneva area [9]. A similar study, CEPC, is led by IHEP in Beijing, about hosting this collider in China [11]. A circular collider at the Higgs threshold would be able to deliver integrated luminosities which are— at the Higgs production threshold—higher by a factor >5 for the same running time and one interaction region, as a linear collider. It could also serve more than one interaction region simultaneously in the recirculating beams, adding up the integrated luminosities of each installed experiment. This is a big advantage over a linear collider, where the colliding beams are used only once and disposed off in beam dumps after the collision. On the other hand, the infrastructure for a 100 km installation becomes very challenging, and the energy reach of a circular machine is limited due to the losses by synchrotron radiation. It is clear that any electron-positron collider that goes beyond 350 GeV has to be linear. In that respect, linear colliders do scale with energy while circular colliders do not.

For the experimenter however the challenges at any of the proposed electron-positron collider facilities are similar. The biggest difference between the proposals is the distance between bunches. At the ILC and FCC-ee (at the Higgs threshold) this time difference is with a few 100 ns very benign. At CLIC bunch distances at sub-ns

level are anticipated, and pose additional challenges to the experiment. Nevertheless, the goals for all facilities are the same: the experiment should be able to do precision physics, even for hadronic final states, should allow the precise reconstruction of charged and neutral particles, of secondary vertices. It has to function with the very large luminosity proposed for these machines, including significant backgrounds from beam-beam interactions.

22.4.1 Physics at an LC in a Nutshell

The design of a detector at a large facility like the ILC or CLIC can not be described nor understood without some comprehension about the type of measurements which will be done at this facility. A comprehensive review of the proposed physics program at the ILC facility can be found in [23, 25, 26], a review of CLIC physics is available under [7, 8].

The discussion in this section concentrates on the physics which can be done at a facility with an energy below 1 TeV. In recent years, the physics reach of a facility operating at around 250 GeV has been closely scrutinised, both at ILC and at CLIC (which is proposed to run in an initial energy stage at 380 GeV). Earlier studies have looked at the science case for a 500 GeV machine, and have explored the additional measurements possible if an energy upgrade up to 1 TeV might be possible.

At a center-of-mass energy of 250 GeV the ILC will be able to create Higgs bosons in large numbers, mostly in the so called Higgs-Strahlungs process. Here a Higgs boson is produced associated to a Z boson. The great power of this process is that by reconstructing the Z, and knowing the initial beam energies, one can reconstruct the properties of the Higgs boson without ever looking at the Higgs boson itself. Thus a model independent and decay mode-blind study of the Higgs particle will become possible. In addition through the reconstruction of exclusive final states for the Higgs particle, high precision measurements of the branching ratios will be possible. On its own, precisions on the most relevant branching ratios of around 1% will be possible. Combined with the results from the LHC, this precision can be pushed to well below the percent level. Samples of the heavy electroweak bosons, *W* and *Z*, a focus of the program at the LEP collider, will in addition be present in large numbers, and might still present some surprises if studied in detail.

If the energy of the facility can be increased to above 350 GeV, top-quark pairs can be produced thus turning the ILC into a top factory. Again, due to the cleanliness of the initial and the final states, high precision reconstruction of the top and its parameters will become possible. A precision scan of the top pair production threshold would determine the top mass with a statistical error of 27 MeV [27], which relates to a relative precision of $\approx 0.015\%$, far better than what can be done at LHC.

Operating at 500 GeV or slightly above, the ILC will gain access to the measurement of the top-Higgs coupling, and start to become sensitive to a measurement

of the Higgs self coupling. This latter experiment might provide evidence for the existence of this interaction at 500 GeV, but would vastly profit from even higher energies. At 1 TeV the Higgs self coupling could be measured to within 10%, which allows for reconstructing the Higgs potential and, thus, testing a cornerstone of the predictions of the standard model and the Higgs sector. Together these measurements will allow a complete test of the Higgs sector, and thus a in-depth probe of the standard model in this unexplored region.

There are good reasons to assume that the standard model is only an effective low-energy theory of a more complex and rich theory. A very popular extension of the standard model is supersymmetry, which predicts many new states of matter. Even though the LHC sofar has not found any evidence for supersymmetry, many models exists which predict new physics in a regime mostly invisible to the LHC. Together ILC and LHC would explore essentially the complete phase space in the kinematic regime accessible at the energy of the ILC.

Should a new state of matter be found at either the LHC or the ILC, electron-positron collisions would allow to study this sign of new physics with great precision.

In addition to direct signs of new physics, as represented by new particles, the ILC would allow to indirectly explore the physics at the Terascale through precision measurements, up to energy scales which in many cases are equivalent if not higher than those at the LHC. It might well be, if no new physics is found at the LHC, that these precision measurements at comparatively low energies are our only way to learn more about the high-energy behaviour of the standard model, and to point at the right energy regime where new physics will manifest itself.

Even though the ILC has been at the focus of the discussions in this chapter, all other electron-positron collider options will have a very similar physics reach—for those energies which are reachable at each facility.

22.5 Experiments at a Lepton Collider

As discussed in the previous section, high energy lepton collisions offer access to a broad range of scientific questions. A hallmark of this type of colliding beam experiments is the high precision accessible for many measurements. A detector at such a facility therefore has to be a multi-purpose detector, which is capable to look at many different final states, at many different signatures and topologies. In this respect the requirements are similar to the ones for a detector at a hadron collider. The direction in which an lepton collider detector is optimised however is very different. Lepton collider detectors are precision detectors—something which is possible because the lepton collider events are comparatively clean, backgrounds are low, and rates are small compared to the LHC. The collision energy at the lepton collider is precisely known for every event, making it possible to measure missing mass signatures with excellent precision. This will make it possible to measure masses of supersymmetric particles with precision, or, in fact, masses of

any new particle within reach of the collider. The final states are clean and nearly background-free, making it possible to determining absolute branching ratios of essentially every state visible at the lepton collider. The reconstruction also of hadronic final states is possible with high precision, opening a whole range of states and decay modes which are invisible at a hadron machine due to overwhelming backgrounds.

This results in a unique list of requirements, and in particular on very high demands on the interplay between different detector components. Only the optimal combination of different parts of the detector can eventually deliver the required performance.

Many of the interesting physics processes at an LC appear in multi-jet final states, often accompanied by charged leptons or missing energy. The reconstruction of the invariant mass of two or more jets will provide an essential tool for identifying and distinguishing W's, Z's, H's, and top, and discovering new states or decay modes. To quantify these requirements the di-jet mass is ofter used. Many decay chains of new states pass through W or Z bosons, which then decay predominantly into two jets. To be able to fully reconstruct these decay chains, the di-jet mass resolution should be comparable or better than the natural decay width of the parent particles, that is, around 2 GeV for the W or Z:

$$\frac{\Delta E_{di-jet}}{E_{di-jet}} = \frac{\sigma_m}{M} = \frac{\alpha}{\sqrt{E\,(\mathrm{GeV})}}, \tag{22.1}$$

where E denotes the energy of the di-jet system. With typical di-jet energies of 200 GeV at a collision energy of 500 GeV, $\alpha = 0.3$ is a typical goal. Compared to the best existing detectors this implies an improved performance of around a factor of two. It appears possible to reach such a resolution by optimally combining the information from a high resolution, high efficiency tracking system with the ones from an excellent calorimeter. This so called particle flow ansatz [28, 29] is driving a large part of the requirements of the LC detectors.

Table 22.3 summarises several selected benchmark physics processes and fundamental measurements that make particular demands on one subsystem or another, and set the requirements for detector performance.

22.5.1 Particle Flow as a Way to Reconstruct Events at a Lepton Collider

Particle flow is the name for a procedure to optimally combine information from the tracking system and the calorimeter system of a detector, i.e. to fully reconstruct events. Particle flow has been one of the driving forces in the optimisation of the detectors at a Lepton Collider.

Typical events at the LC are hadronic final states with Z and W particles in the decay chain. In the resulting hadronic jets, typically around 60% of all stable

Table 22.3 Sub-Detector performance needed for key LC physics measurements (from [30])

Physics process	Measured quantity	Critical system	Critical detector characteristic	Required performance
ZHH $HZ \rightarrow q\bar{q}b\bar{b}$ $ZH \rightarrow ZWW^{*}$ $\nu\bar{\nu}W^{+}W^{-}$	Triple Higgs coupling Higgs mass B$(H \rightarrow WW^{*})$ $\sigma(e^{+}e^{-} \rightarrow \nu\bar{\nu}W^{+}W^{-})$	Tracker and calorimeter	Jet energy resolution, $\Delta E/E$	$3 \sim 4\,\%$ or $30\%/\sqrt{E}$
$ZH \rightarrow \ell^{+}\ell^{-}X$ $\mu^{+}\mu^{-}(\gamma)$ $ZH + H\nu\nu \rightarrow \mu^{+}\mu^{-}X$	Higgs recoil mass luminosity weighted E_{cm} B$(H \rightarrow \mu^{+}\mu^{-})$	Tracker	Charged particle momentum resolution, $\Delta p_{t}/p_{t}^{2}$	5×10^{-5}
HZ, $H \rightarrow b\bar{b}$, $c\bar{c}$, gg $b\bar{b}$	Higgs branching fractions b quark charge asymmetry	Vertex detector	Impact parameter, δ_{b}	$5\,\mu\mathrm{m} \oplus$ $10\,\mu\mathrm{m}/p(\mathrm{GeV}/c)\sin^{3/2}\theta$

particles are charged, slightly less than 30% are photons, only around 10% are neutral long lived hadrons, and less than 2% are neutrinos. At these energies charged particles are best re-constructed in the tracking system. Momentum resolutions which are reached in detectors are $\delta p/p^2 \approx 5 \times 10^{-5}\,\mathrm{GeV}^{-1}$, much better than any calorimeter system at these energies. Electromagnetic energy resolutions are around $\delta E_{em}/E = 0.15/\sqrt{E}(\mathrm{GeV})$, typical resolutions achieved with a good hadronic calorimeter are around $\delta E_{had}/E = 0.45/\sqrt{E}(\mathrm{GeV})$. Combining these with the proper relative weights, the ultimate energy resolution achievable by this algorithm is given by

$$\sigma^2(E_{jet}) = w_{tr}\sigma_{tr}^2 + w_\gamma \sigma_\gamma^2 + w_{h^0}\sigma_{h^0}^2, \tag{22.2}$$

where w_i are the relative weights of charged particles, photons, and neutral hadrons, and σ_i the corresponding resolution. Using the above mentioned numbers an optimal jet mass resolution of $\delta E/E = 0.16/\sqrt{E}(GeV)$ can be reached. This error is dominated by the contribution from the energy resolution of neutral hadrons, assumed to be $0.45/\sqrt{E}(GeV)$. This formula assumes that all different types of particles in the event can be individually measured in the detector. This implies that excellent spatial resolution in addition to the energy resolution is needed. Thus fine-grained sampling calorimeters are the only option currently available which can deliver both spatial and energy resolution at the same time. This assumption is reflected in the resolution numbers used above, which are quoted for modern sampling type calorimeters. Even though an absorption-type calorimeter— for example a crystal calorimeter as used in the CMS experiment—can deliver better energy resolution, it falls significantly behind in the spatial resolution, thus introducing a large confusion term in the above equation.

Formula 22.2 describes a perfect detector, with perfect efficiency, no acceptance holes, and perfect reconstruction in particular of neutral and charged particles in the calorimeter. In reality a number of effects result in a significant deterioration of the achievable resolution. If effects like a final acceptance of the detector, missing energy e.g. from neutrinos etc. is included, this number easily increases to $25\%/\sqrt{E}$ [31]. All this assumes that no errors are made in the assignment of energy to photons and neutral hadrons. The optimisation of the detector and the calorimeter in particular has to be done in a way that these wrong associations are minimised.

From the discussion above it is clear that three effects are of extreme importance for a detector based on particle flow: as good hadronic energy resolution as possible, excellent separation of close-by neutral and charged particles, and excellent hermeticity. It should also be clear that the ability to separate close-by showers is more important than ultimate energy resolution: it is for this reason that total absorption calorimeters, as used e.g. in the CMS experiment, are not well suited for the particle flow approach, as they do not lend themselves to high segmentation.

Existing particle flow algorithms start with the reconstruction of charged tracks in the tracking system. Found tracks are extrapolated into the calorimeter, and linked with energy deposits in there. If possible, a unique assignment is made between a track and an energy deposit in the calorimeter. Hits in the calorimeter belonging

to this energy deposit are identified, and are removed from further considerations. The only place where the calorimeter information is used in the charged particle identification is in determining the type of particle: calorimeter information can help to distinguish electrons and muons from hadrons. A major problem for particle flow algorithms are unassigned clusters, and mis-assignments between neutral and charged deposits in the calorimeter. The currently most advanced particle flow algorithm, PandoraPFA, tries to minimise these effects by a complex iterative procedure, which optimises the assignments, goes through several clean-up steps, and tries to also take the shower sub-structure into account [31].

What is left in the calorimeter after this procedure is assumed to have come from neutral particles. Clusters in the calorimeter are searched for and reconstructed. With a sufficiently high segmentation both transversely and longitudinally, the calorimeter will be able to separate photons from neutral hadrons by analysing the shower shape in three dimensions. A significant part of the reconstruction will be then the reconstruction of the neutral hadrons, which leave rather broad and poorly defined clusters in the hadronic calorimeter system.

Particle flow relies on a few assumptions about the event reconstruction. For it to work it is important that the event is reconstructed on the basis of individual particles. It is very important that all charged tracks are found in the tracker, and that the merging between energy deposits in the calorimeter and tracks in the tracker is working as efficiently as possible. Errors in this will quickly produce errors for the total energy, and in particular for the fluctuations of the total energy measured. Not assigning all hits in the calorimeter to a track will also result in the creating of additional neutral clusters, the so called double counting of energy. Reconstructing all particles implies that the number of cracks and the holes in the acceptance should be minimised. This is of particular importance in the very forward direction, where the reconstruction of event properties is complicated by the presence of backgrounds. However, small errors in this region will quickly introduce large errors in the total energy of the event, since many processes are highly peaked in the forward direction.

In Fig. 22.5 the performance of one particular particle flow algorithm, PandoraPFA [31] is shown, as a function of the dip angle of the jet direction, $\cos\theta$. The performance for low energies of the jets, 45 GeV is close to the optimally possible resolution if the finite acceptance of the detector is taken into account. At higher energies particles start to overlap, and the reconstruction starts to pick up errors in the assignment between tracks and clusters. This effect, called confusion, will deteriorate the resolution, and will increase at higher energies. Jets at higher energies are boosted more strongly, resulting in smaller average distances between particles in the jet. This results in a worse separation of particle inside the jet, and thus a worse resolution. Figure 22.6 shows an event display of a simulated hadronic jet in the ILD detector concept for the ILC with particle flow objects reconstructed by PandoraPFA. The benefit of a highly granular detector system is clearly visible.

Over the last 10 years, the Pandora algorithm has matured into a robust and stable algorithm. It is now used not only in the linear collider community, but also in long baseline neutrino experiments, and is under study at the LHC experiments.
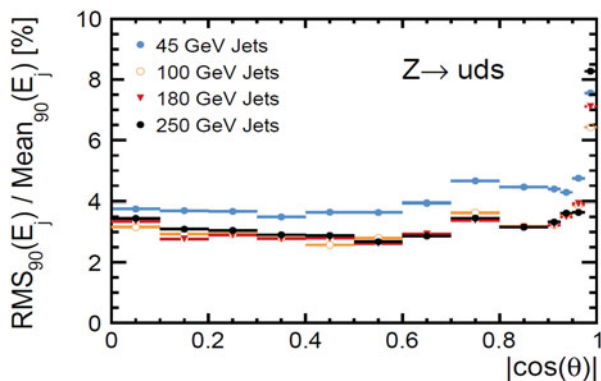
Fig. 22.5 The jet energy resolution, α, as a function of the dip angle $|\cos\theta_q|$ for jets of energies from 45 GeV to 250 GeV
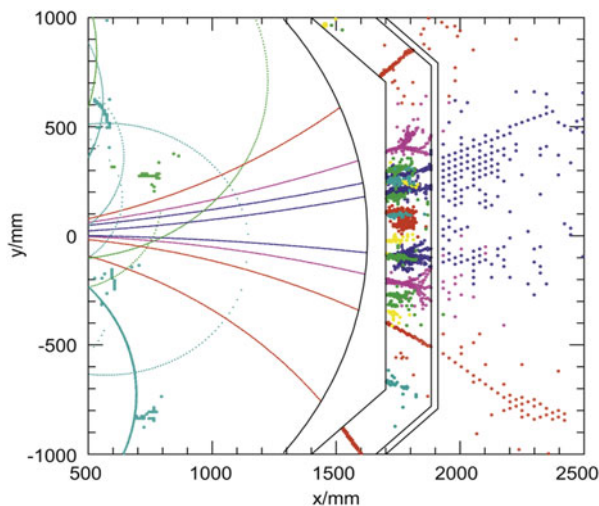

Fig. 22.6 Simulated jet in the ILD detector, with particle flow objects reconstructed by the Pandora algorithm shown in different colors

22.5.2 A Detector Concept for a Lepton Collider

Over the years a number of concepts for integrated detectors have been developed for use at a lepton collider [32–36]. Broadly speaking two different models exist: one based on the assumption, that particle flow is the optimal reconstruction technique, the other not based on this assumption. Common to all proposals is that both the tracking system and the calorimeter systems are placed insides a large superconducting coil which produces a large magnetic field, of typically 3–5 T. Both concepts use high precision tracking and vertexing systems, inside solenoidal

fields, which are based on state of the art technologies, and which really push the precision in the reconstruction of the track momenta and secondary vertices. Differences exist in detail in the choice of technology for the tracking devices, some rely heavily on silicon sensors, like the LHC detectors, others propose a mixture of silicon and gaseous tracking. The calorimeters are where these detectors are most different from current large detectors. The detectors based on the particle flow paradigm propose calorimeters which are more like very large tracking systems, with material intentionally introduced between the different layers. Systems of very high granularity are proposed, which promise to deliver unprecedented pictures of showering particles. Another approach is based on a more traditional pure calorimetric approach, but on a novel technology which promises to eventually allow the operation of an effectively compensated calorimeter [34].

At the ILC, detectors optimised for particle flow have been chosen as the baseline. The two proposed detector concepts ILD [32] and SiD [33] differ in the choice of technology for the tracking detectors, and on the overall emphasis based on particle flow performance at higher energies. However, both detectors have been optimised for collision energies of less than 1 TeV, while within the CLIC study the detector concepts have been further evolved to be optimised for operation at energies up to 3 TeV [35].

A conceptual picture of the ILD detector, as proposed for the ILC, is shown in Fig. 22.7. Visible are the inner tracking system, the calorimeter system inside the coil, the large coil itself, and the iron return yoke instrumented to serve as a muon identification system. A cut view of a quadrant with the sub-systems of ILD is shown in Fig. 22.8.
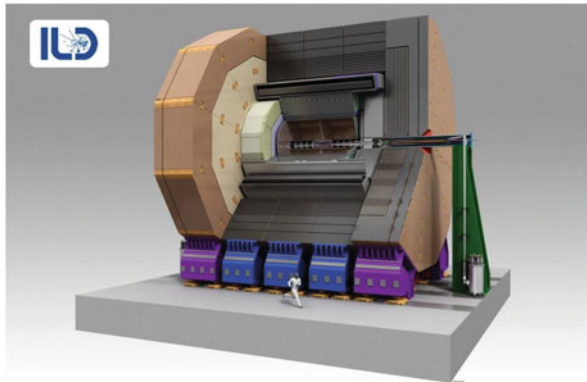

Fig. 22.7 Three-dimensional view of a proposed detector concept for the ILC, the ILD detector [32] (credit Ray Hori, KEK)
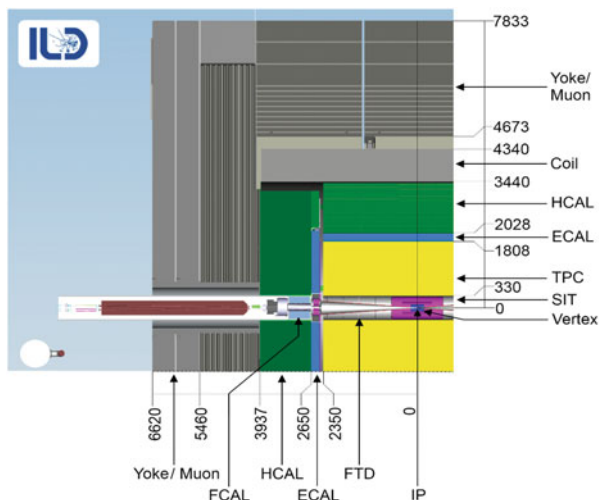
Fig. 22.8 Cut through the ILD detector in the beam plane, showing one quarter of the detector [37]

22.6 Detector Subsystems

A collider detector has a number of distinct sub-systems, which serve specific needs. In the following the main systems are reviewed, with brief descriptions of both the technological possibilities, and the performance of the system.

22.6.1 Trends in Detector Developments

Detector technologies are rapidly evolving, partially driven by industrial trends, partially itself driving technological developments. New technologies come into use, and disappear again, or become accepted and well-used tools in the community. A challenge for the whole community is that technological trends change faster than ever, while the design, construction and operation cycles of experiments become longer. Choosing a technology for a detector therefore implies not only using the very best available technology, but also one which promises to live on during the expected lifetime and operational period of the experiment. An example of this are Silicon technologies, which are very much driven by the demands of the modern consumer electronics industry. By the times Si detectors are operational inside an experiment, the technology used to built them is often already outdated, and replacements or extensions in the same technology are difficult to get. Even more so than to the sensors this applies to readout and data acquisition systems.

Because of the rapid progress in semiconductor technology, feature sizes in all kind of detector are getting ever smaller. Highly integrated circuits allow the integration of a great deal of functionality into small pixels, allowing the pixellation of previously unthinkable volumes. This has several consequences: the information about an event, a particle, a track, becomes ever larger, with more and more details at least potentially available and recorded. More and more the detection of particles, of properties of particles, rely no longer on averaging its behaviour over a volume large compared to the typical distances involved in the process used to measure the particle, but allows the experimenter to directly observe the processes which eventually lead to a signal in the detector. Examples of this are e.g. the Si-TPC (Silicon readout Time Projection Chamber, described in more detail below) where details of the ionisation process of a charged particle traversing a gas volume can be observed, or the calorimeter readout with Si-based pixellated detectors, given unprecedented insights into the development of particle showers. Once the volume read out becomes small compared to the typical distances involved in the process which is being observed, a digital readout of the information can be contemplated. Here, only the density of pixels is recorded, that is, per pixel only the information whether or not a hit has occurred, is saved. This results in potentially a much simpler readout electronics, and in more stable and simpler systems. These digital approaches are being pursued by detectors as different as a TPC and a calorimeter.

Increasing readout speed is another major direction of developments. It is coupled but not identical to the previously discussed issue of smaller and smaller feature sizes of detectors. Because of the large number of channels, faster readout systems need to be developed. An even more stringent demand however comes from the accelerators proposed, and the luminosities needed to make the intended experiments. They can only be used if data are readout very quickly, and stored for future use. To give a specific example: the detector with the largest numbers of pixels ever built so far (until the Phase-II upgrades of the LHC detectors) has been the SLD detector at SLAC which operated during the 1990. The vertex detector, realised from charged coupled sensors with some 400 Million channels, was readout with a rate of around 1 MHz. For the ILC readout speeds of at least 50 MHz, maybe even more, are considered, to cope with larger data rates and smaller inter-bunch spacings.

Technological advances in recent years have made it feasible to consider the possibility to do precision timing measurements with semi-conductor detectors. Timing resolutions in the range of 100 ps or better are becoming feasible, something completely unthinkable only a few years ago. This capability—somewhat orthogonal to the readout speed discussed above—can significantly extend the capabilities of semiconductor tracker, into the direction of so-called 4D tracking or calorimeter systems. Timing information at this level of precision can be used to measure the mass of particles through time-of-flight, and can help to separate out-of-time background from collision related events.

For many applications, particularly at the LHC, radiation hardness is at a premium. Major progress has been made in recent years in understanding damage mechanisms, an understanding, which can help to design better and more radiation hard detectors. For extreme conditions novel materials are under investigation.

22.6.2   *Vertex Detectors: Advanced Pixel Detectors*

Many signals for interesting physics events include a long lived particle, like e.g. a B or charmed hadron, with typical flight distances in the detector from a few 10 µm to a few mm. The reconstruction of the decay vertices of these particles is important to identify them and to distinguish their decay products from particles coming from the primary vertex, or to reconstruct other event quantities like vertex charge.

To optimally perform these functions the vertex detector has to provide high precision space points as close as possible to the interaction point, has to provide enough space points, so that an efficient vertex reconstruction is possible over the most relevant range of decay distances, of up to a few cm in radius, and present a minimal amount of material to the particle so as to not disturb their flight path. Ideally, the vertex detector also offers enough information that stand-alone tracking is possible based only on vertex detector hits.

At the same time a vertex detector has to operate stably in the beam environment. At a hadron collider it has to stand huge background rates, and cope with multiple interactions. At a lepton collider, very close to the interaction point a significant number of beam background particles may traverse the detector, mostly originating from the beam–beam interaction. These background particles are bent forward by the magnetic field in the detector. The energy carried away by this beamstrahlung may be several 10 TeV, which, if absorbed by the detector, would immediately destroy the device. The exact design of the vertex detector therefore has to take into account these potential backgrounds. At a hadron collider, the largest challenge will be to design the detector such that it can survive the radiation dose and is fast enough and has small enough pixels to cope with the large particle multiplicity. Here pixel size, readout speed, and radius of the detector are the main parameters which need to be optimised. At a lepton collider, both size and magnetic field can be used to make sure that the detector stays clear of the majority of the background particles. The occupancy at any conceivable luminosity is not driven by the physics rate, but only by the background events. Since they are much softer than the physics events, a strong magnetic field can be used to reduce the background rates, and allow small inner radii of the system. Nevertheless, the remaining hits from beam background particles dominate the occupancies, especially at the innermost layers of a vertex detector, and therefore require fast read-out speeds.

The particular time structure of the collider has an important impact on the design and the choice of the technology. At the ILC collisions will happen about every 300 ns to 500 ns, in a train of about 1 ms length, followed by a pause of around 200 ms. About 1300 bunches are expected to be in one train. A fast readout of the vertex detector is essential to ensure that only a small number of bunches are superimposed within the occupancy of the vertex detector. At CLIC the inter-bunch spacing is much smaller, putting a premium on readout speed. At LHC the typical time between collisions in a bunch crossing is order 100 ps decreasing to about 10 ps at the high luminosity LHC-HL.

A Si-pixel based technology is considered the only currently available technology which can meet all these requirements. A small pixel size ($< 20 \times 20\,\mu m^2$) combined with a fast read out will ensure that the occupancy due to backgrounds and from expected signals together remain small enough to not present serious reconstruction problems. It also allows for a high space point resolution, and a true three dimensional reconstruction of tracks and vertices essentially without ambiguities. Several silicon technologies are available to meet the demands. Increasingly, sensors based on the CMOS process are considered. Most recently devices with intrinsic gain larger than one are studied intensely, as they promise excellent performance combined with very good timing properties.

Quite a number of different technologies are currently under study. Broadly they can be grouped into at least two categories: those which try to read the information content as quickly as possible, and those which try to store information on the chip, and which are readout during the much longer inter-bunch time window. Another option under study is a detector with very small pixels, increasing the number of pixels to a point where even after integration over one full bunch train the overall occupancy is still small enough to allow efficient tracking and vertexing.

A fairly mature technology is the CCD technology [38, 39], which for the first time was very successfully used at the SLD experiment at the SLC collider at SLAC, Stanford. Over the past decade a number of systems based on this concept have been developed.

Newer approaches use the industrial CMOS process to develop monolithic active pixel sensors (MAPS) that are at the same time thin, fast, and radiation hard enough for particle physics experiments [40]. A smaller scale application of this technology is a series of test-beam telescopes, based on the Mimosa families of chips [41], built under the EUDET and AIDA European programs [42, 43] and operated a CERN, DESY and SLAC. The Phase-II upgrade of the ALICE experiment at the LHC contains a new inner tracking system that will be completely based on the CMOS-MAP sensor ALPIDE [44]. With a pixel size of $24.9\,\mu m \times 29.3\,\mu m$, a spatial resolution of $\approx 5\,\mu m$ and a time resolution of $5–10\,\mu s$ is envisaged for hit rates of about $10^6/cm^2/s$. The CBM experiment, planned for the FAIR heavy-ion facility in Darmstadt, foresees to use MAPS for the microvertex detector. It will be based on the MIMOSIS chip, that is an advancement of the ALPIDE chip with similar pixel size and spatial resolution, but that has to cope with a much higher event rate of about $10^8/cm^2/s$ (and the associated radiation load) at the cost of a higher power consumption. The MIMOSIS chip already aims for a higher readout speed of about $5\,\mu s$.

In Fig. 22.9 a measured point resolution achieved with the CMOS-MAPS technology in a test beam experiment is shown [49]. Other technologies are at a similar level of testing and verifying individual sensors for basic performance.

Studies are underway to push the CMOS-MAPS towards even higher readout speeds [45]. The two parameters that currently govern the process are the time required for the pixel address encoding and the signal shaping during the pre-amplification. Changing the algorithm of the pixel address encoding and increasing the internal clock, could lead to an improvement from 50 ns to 25 ns for this step.
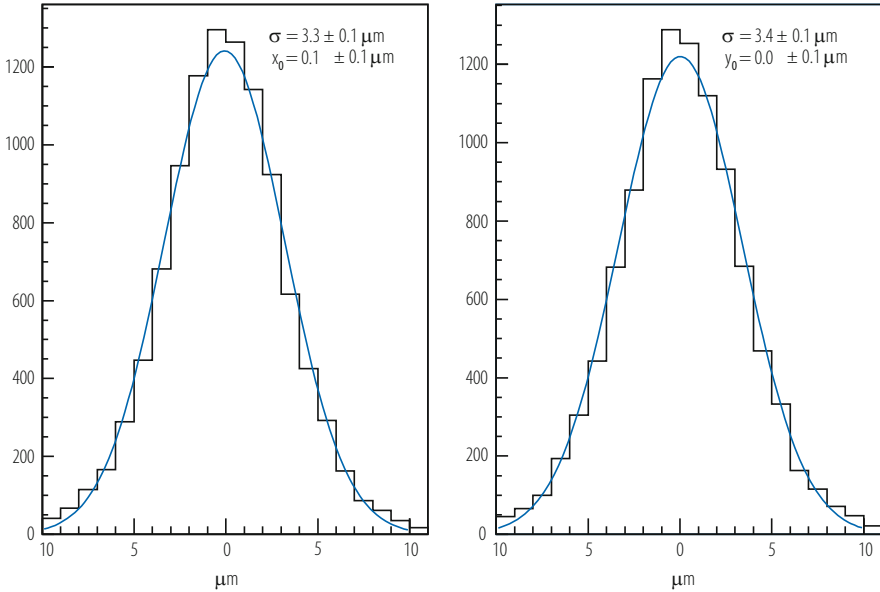
Fig. 22.9 (Left): Biased residual distribution measured in a CMOS pixel detector with 6 GeV electrons. (Right) Measured residual width in a 6 layer setup with a layer spacing of 20 mm [49]

The signal shaping currently takes about 2 μs and could be shortened to about 500 ns at the price of increasing the pixel current and therefore also increasing the power consumption. However, as the detectors at a linear collider would be operated in power-pulsing mode, the impact on the cooling requirements would be minor. Such an optimised CMOS detector for the ILC would have a readout speed of about 1 μs, i.e. it could be read out every two to three bunch crossings. Other groups explore the possibility to store charge locally on the pixel, by including storage capacitors on the pixel. Up to 20 timestamped charges are foreseen to be stored, which will then be readout in between bunch trains.

The most recent example of a pixel detector at a lepton collider has been the pixel detector for the Belle-II experiment. This system is based on the DEPFET technology [46]. Charge generated by the passage of a charged particle through the fully depleted sensitive layer is collected on the gate of a DEPFET transistor, implemented into each pixel. DEPFET sensors can be thinned to remove all silicon not needed for charge collection, to something like 50 μm, or 0.1% of a radiation length. This makes this technology well suited for lepton collider applications, where minimal material is of paramount importance [48].

A problem common to all technologies considered is the amount of material present in the detector. A large international R&D program is under way to reduce significantly the material needed to build a self-supporting detector. The goal, driven by numerous physics studies, and the desire for ultimate vertex reconstruction, is a single layer of the detector which in total presents 0.1% of a radiation length,

including sensor, readout and support. This can only be achieved by making the sensors thin, and by building state-of-the-art thin and light weight support structures. To compare, at the LHC the total amount of material present in the silicon based trackers is close to 2 radiation length, implying that per layers, close to 10% of a radiation length is present.

Very thin sensor layers are possible with technologies based on fully depleted sensors. Since here only a thin layer of the silicon is actually needed for the charge collection the rest of the wafer can be removed, and the sensor can be thinned from typically 300 μm, used e.g. in the LHC experiments, to something like 50 μm or less. Several options are under study how such thin Si-ladders can then be supported. One designs foresees that the ladders be stretched between the two endcaps of the detectors, being essentially in the active area without additional support. Another approach is to study the use of foam material to build up a mechanically stiff support structure. Carbon foam is a prime candidate for such a design, and first prototype ladders have come close to the goal of a few 0.1% X_0 [47]. Another group is investigating whether Si itself could be used to provide the needed stability to the ladder. By a sophisticated etching procedure stiffening ribs are built into the detector, in the process of removing the material from the backside, which will then stabilise the assembly. This approach has been successfully implemented for the vertex detector at the Belle-II experiment [48].

Material reduction is an area where close connections exist between developments done for the ILC and developments done for the LHC and its upgrade. In both cases minimum material is desired, and technologies developed in the last few years for the ultra-low material ILC detector are of large interest to possible upgrade detectors for LHC and LHC Phase-II.

The readout of these large pixel detectors present in itself a significant challenge. On-chip zero-suppression is essential, but also well established. Low power is another important requirement, consistent with the low mass requirement discussed above. Only a low power detector can be operated without liquid cooling, low mass can only be achieved without liquid cooling. It has been estimated that the complete vertex detector of an ILC detector should not consume on average more than 100 W, if it is to be cooled only through a gas cooling system. Currently this is only achievable if the readout electronics located on the detector is switched off for a good part of the time, possible with the planned bunch structure of the ILC. However such a large system with pulsed power has never been built, and will require significant development work. It should not be forgotten that the system needs to be able to operate in a large magnetic field, of typically 4 T. Each switching process therefore, which is connected with large current flows in the system, will result in large Lorentz forces on the current leads and the detectors, which will significantly complicate the mechanical design of the system. Nevertheless, with current technologies power pulsing is the only realistic option to achieve the desired low power operation, and thus a central requirement for the low mass design of the detector. In Fig. 22.10 the conceptual layout of a high precision vertex detector is shown.
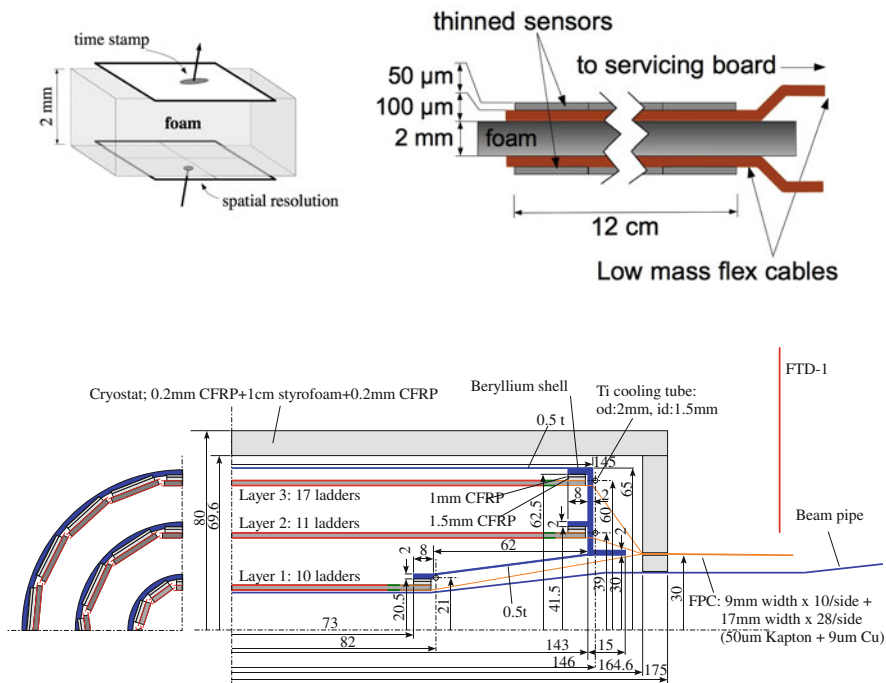
Fig. 22.10 Top: Concept of a double-layer vertex detector system developed within the PLUME project. Bottom: Vertex detector for the ILD concept, based on a layout with three double layers [37]

One of the key performance figures of a vertex detector is its capability to tag heavy flavours. At the ILC b-quarks are an important signature in many final states, but more challenging are charm quarks as the are e.g. expected in decays of the Higgs boson. Obtaining a clean sample of charm hadrons in the presence of background from bottom and light flavour is particularly difficult. Already at the SLC and the LEP collider, the ZVTOP [50] algorithm has been developed and used successfully. It is based on a topological approach to find displaced vertices. Most tracks originating from heavy flavour decays have relatively low momenta, so excellent impact parameter resolution down to small ($\approx$1GeV) energies is essential. On the other hand, due to the large initial boost of the heavy hadrons, the vertices can be displaced by large distances, up to a few cm away from the primary vertex, indicating that the detector must be able to reconstruct decay vertices also at large distances from the interaction point. The algorithms have been further developed and adapted to the expected conditions at a linear collider [51]. The performance of a typical implementation of such a topological vertex finder is shown in Fig. 22.11.
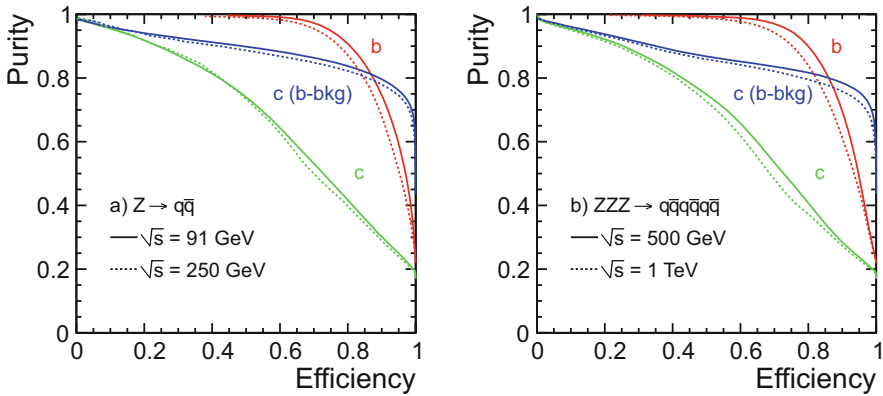
Fig. 22.11 Purity versus efficiency curve for tagging b-quarks (red points) and c-quarks (green points) and c-quarks with only b-quark background (blue points) obtained in a simulation study for Z-decays into two (left) and six (right) jets, as simulated in the ILD detector [37]

22.6.3 Solid State Tracking Detectors: Strip Detectors

To determine the momentum of a charged particle with sufficient accuracy, a large volume of the detector needs to be instrumented with high precision tracking devices, so that tracks can be reliably found and their curvature in the magnetic field can be well measured. Cost and complexity considerations make a pixel detector for such large scale tracking applications at present not feasible. Instead strip detectors are under development, which will provide excellent precision in a plane perpendicular to the electron-positron beam.

Silicon microstrip detectors are extremely well understood devices, which have been used in large quantities in many experiments, most recently on an unprecedented scale by the LHC experiments. A typical detector fabricated with currently established technology might consist of a 300 μm thick layer of high resistivity silicon, with strips typically every 50 μm running the length of the detector. Charge is collected by the strips. These detectors measure one coordinate very well, with a precision of <10 μm. The second coordinate can be measured e.g. by arranging a second layer of strip detectors at a small stereo angle. Double sided detectors, with two readout structures on either side, with strips running also at an angle to each other, have in the past proved to be a costly and not very reliable alternative to the combination of two single sided detectors back-to-back.

Strip detector have received a major boost through the upgrade program for the LHC experiments. The large area tracking systems for both ATLAS and CMS will need to be replaced in time for the start of the high luminosity phase of the LHC, scheduled to start around 2026. Several hundred square meters of Silicon detectors need to be produced, to build up these large detector systems. Compared to the previous ones, the radiation hardness of these devices had to be improved by at least an order of magnitude, and the total amount of material in the system will be reduced

significantly. This requires novel approaches to the structures, and to powering and cooling of these detectors, which will be discussed in a separate section.

A major R&D goal needed for the application of these devices to the ILC detector is the significant reduction of material per layer. As for the vertex pixel detector, thinning the detectors is under investigation, as is the combination of thinned detectors with light weight support structures and power-pulsed readout electronics. New schemes to deliver power to the detectors—like serial powering—are being studied.

22.6.4 Gaseous Tracking

Even though solid state tracking devices have advanced enormously over the last 20 years, gaseous tracking is still an attractive option for a high precision detector like an ILC detector. Earlier in this section the concept of particle flow has been discussed. Particle flow requires not the very best in precision from a tracking detector, but ultimate efficiency and pattern recognition ability. Only if charged tracks are found with excellent efficiency can the concept of particle flow really work. A large volume gaseous tracker can assist in this greatly by providing a large number of well measured points along a track, over a large volume. In addition a gaseous detector can assist in the identification of the particle by measuring the specific energy loss, dE/dx, of the particle, which for moderate momenta up to 10–20 GeV is correlated to the particle type.

A particularly well suited technology for this is the time projection chamber, TPC [52]. It has been used in the past very successfully in a number of colliding beam experiments, most recently in the ALICE experiment at the LHC [53]. A time projection chamber (see Chapt. C1 ii) essentially consists of a volume of gas, onto which a uniform electric and magnetic field is superimposed. If a charged particle crosses the volume, the produced ionisation is drifted under the influence of the field to the anode and the cathode of the volume. Since the electrons drift typically about 1000 times faster than the ions, they are usually used in the detection. A gas amplification system at the anode side is used to increase the available charge which is then detected on a segmented anode plane, together with the time of arrival. Combining both, a three dimensional reconstruction of the original crossing point is possible.

Traditionally time projection chambers are read out at the anode with multi-wire proportional chambers. They operate reliably, have a good and well controllable gas gain, and give large and stable signals. However wires are intrinsically one dimensional, which means, that a true three-dimensional reconstruction of the space point is difficult. Wires need to be mechanically stretched, which restricts the distance between them to something larger than typically 1 mm. More importantly though, the fact that all electrons produced in the drift volume are eventually collected by these wires, and that this collection happens in a strong magnetic field, limits the achievable resolution. Very close to the wire the electric field lines and the

magnetic field lines are no longer parallel, and the particle will start to deviate from the ideal straight track toward the anode. It will start to see a strong Lorentz force, which will tend to distort the drift path. This distortions will be different whether the electron approaches the wire from below or from above, and will introduce biases in the reconstruction of the space coordinate which might be similar in size to the spacing between the wires. Corrections might be applied, and can correct in part this effect, but typical uncertainties around 1/10 of the inter-wire distance might remain. This does limit the ultimately achievable resolution in a wire-equipped TPC.

An alternative which is being studied intensely is the use of micro-pattern gas detectors as readout systems in a TPC [54]. Gas electron multipliers (GEM) [55, 56] or Micro Mesh Chambers Micromegas (MM) [57, 58] are two recent technologies under investigation.

A GEM foil consists of a Polyamide foil of a typical thickness of 50–100 μm, copper clad on both sides. A regular grid of holes of 50 μm diameter spaced typically 150 μm apart connects the top and the bottom side. With a potential of a few hundred volts applied across the foil a very high field develops inside the hole, large enough for gas amplification. Gains in excess of 10^3 have been achieved with such setups. In Fig. 22.12 the cross section of a hole in a GEM is shown, together with field lines, showing clearly the high field region in the center of the hole. A challenge for the GEM based system is the development of a mechanically stable readout system. A system based on ceramic spacer structures has been developed and successfully tested [61].

A MM is constructed by stretching a metal mesh with a very fine mesh size across a readout plane, at a distance of typically less than 1 mm from the readout plane. A potential is applied between the mesh and the readout plane. The resulting field is large enough for gas amplification. Spacers at regular intervals ensure that the system is mechanically stable, and withstands the electrostatic forces.

Both systems have feature sizes which are one order of magnitude smaller than the ones in conventional wire-based readout systems, thus reducing the potential errors introduced through the gas amplification system. The smaller feature sizes in addition reduce the spatial and temporal spread of the signals arriving at the readout structure, thus promising a better two particle separation. The spatial resolution obtained in a prototype TPC equipped with a Micromegas readout is shown in Fig. 22.13.

The positive ions which are produced both in the initial ionisation along the track, and in the amplification process at the anode, will drift slowly to the cathode. Thus, the drift volume of the TPC will slowly fill with positive charge, if nothing is done, which will tend to change the space-to-time relation central to the TPC principle. Both GEM and MM suppress the drift of positive ions to the cathode, by catching a large percentage (over 98%) on the GEM foil or on the mesh [60]. To reduce the amount of positive ions even further a gating electrode can be considered. This is an electrode mounted on top of the last amplification stage, facing towards the drift volume. The potential across the gate can be changed to change the transparency of the gate for ions. At the ILC the gate can be opened for one complete bunch train, and then be closed for the inter-bunch time. This would reduce the volume affected by significant ion densities to only the first few cm in drift, above the readout plane.
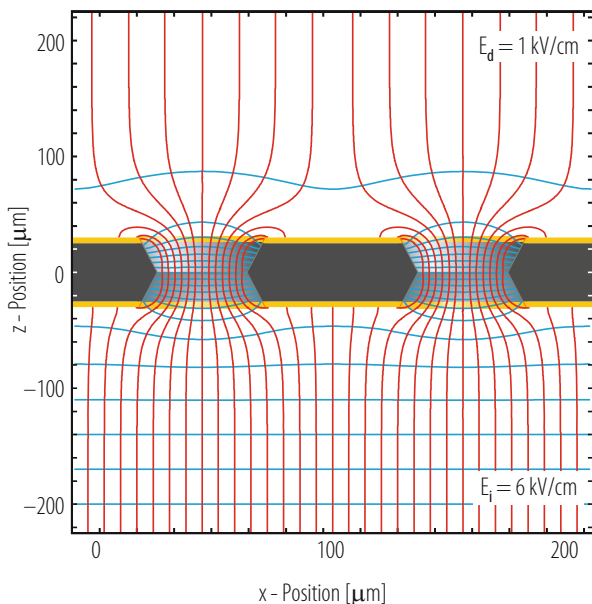
Fig. 22.12 Cross section of a hole in a GEM foil, with simulated field lines (picture credit Oliver Schäfer, DESY)
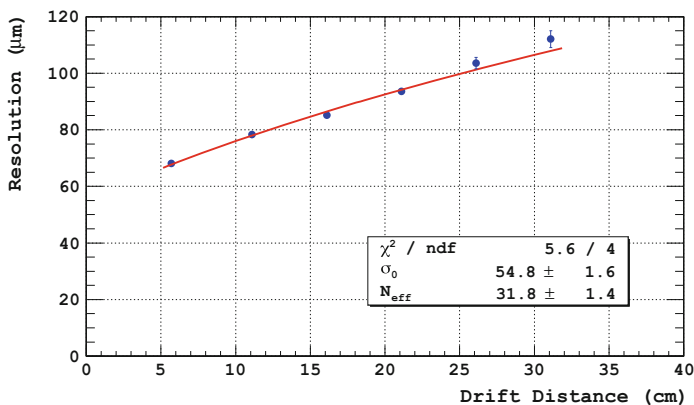

Fig. 22.13 Preliminary result of the spatial resolution of Micromegas readout as a function of drift length. A resistive pad plane was used to spread the charge [59]

Recently specialised GEM foils have been developed, which show a very large optical transparency. Experimentally is has been shown that such devices allow a large change in electron transparency, from close to 90% to 0%, by changing the potential across the GEM by some 50 V. This is expected to translate into a very similar change in ion-transparency, but the final experimental proof for this is still missing.
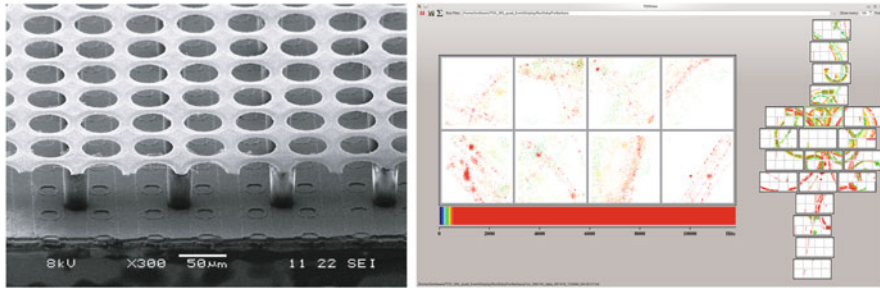
Fig. 22.14 Left: Microscopic picture of an Ingrid: a micromegas detector implemented on top of the read out chip by post-processing; Right: Event display of test beam electrons in a Pixel-TPC setup with Ingrids and Micromegas readout [62] (Credit Michael Lupberger, Bonn)

A recent development tries to combine the advantages of a micro-pattern gas detector with the extreme segmentation possible from silicon detectors. A Si pixel detector is placed at the position of the readout pad plane, and is used to collect the charge behind the gas amplification system. Each pixel of the readout detector has a charge sensitive amplifier integrated, and measures the time of arrival of the signal. Such a chip was originally developed for medical applications (MediPIX [63]), without timing capability, and has since been further developed to also include the possibility to record the time (Timepix [64]). This technology, which is still in its infancy, promises exciting further developments of the TPC concept. The close integration of readout pad and readout electronics into one pixel allows for much more compact readout systems, and also for much smaller readout pads. Pad sizes as small as $50 \times 50\,\mu\mathrm{m}$ have been realised already. This allows a detailed reconstruction of the microscopic track a particle leaves in the TPC, down to the level of individual ionisation clusters. First studies indicate that a significantly improved spatial resolution can be obtained through silicon pixel readout of the TPC. In Fig. 22.14 a picture of a track segment recorded in a small test setup equipped with a Micromegas and the Medipix chip is shown.

The size of charge clouds in a typical TPC is of the order of a few hundred μm to mm, depending on the choice of gas, on environmental parameters like pressure and magnetic field, and on the drift distance. The feature size of the proposed silicon based readout is significantly smaller than this, which may allow the operation of the TPC in a different mode, the so called digital TPC mode. In this case no analogue information about the size of the charge collected at the anode is recorded, but instead only the number and the distribution of pixels which have fired are saved. The distribution of the hits is used to reconstruct the position of the original particle, much as it is done in the case of a conventional TPC. It can be shown that as long as the pixel size is small compared to the size of the electron cloud the number of pixels is a good measure for both the position of the cluster and the total charge in the cluster. One advantage of recording only the number of hits is that the sensitivity to delta rays is reduced. Delta rays are energetic electrons which are kicked out of a

gas molecule by the interaction with the incoming particle, and which then rapidly loose energy in the gas. Delta rays produce large charge clusters along the track, which are not correlated any more with the original particle. They also produce charge some distance away from the original track, and thus limit the intrinsic spatial resolution. Altogether delta rays are responsible for the tails in the charge distribution along a particle track, and for a deterioration of the possible spatial resolution. In digital readout mode these effects are less pronounced. The tails in the charge distribution are reduced, and the excellent spatial resolution through small pads allows the removal of at least some delta rays on a topological basis. Recent studies indicate that the spatial resolution of a Si based TPC readout might be better by about 30%, while the capability to measure the specific energy loss, dE/dx, might increase by 10–20% [65].

22.6.5   Electromagnetic Calorimeters

The concept of particle flow discussed above requires an excellent granularity in the calorimeters to separate charged from neutral particles in the calorimeter. Some hypothetical New Physics scenarios are associated with event topologies where high energetic photons do not originate at the interaction region, so that the device should in addition be able to also reconstruct the direction of a photon shower with reasonable accuracy.

Electromagnetic calorimeters (ECAL) are designed as compact and fine-grained sandwich calorimeters optimised for the reconstruction of photons and electrons and for separating them from depositions of hadrons. Sandwich calorimeters are the devices of choice, since they give information on the development of the cluster both along and transverse to the direction of the shower development. This capability is very difficult to realise with other technologies, and is essential to obtain an excellent spatial reconstruction of the shower. To keep the Moliére radius small, tungsten or lead are used as absorber. Sensor planes are made of silicon pad diodes, Monolithic Active Pixel sensors (MAPS) or of scintillator strips or tiles.

A major problem of fine-grained calorimeters is one of readout and data volume. For a typical electromagnetic calorimeter considered for the ILC, where cell sizes of $5 \times 5 \, mm^2$ are investigated, the number of channels quickly passes the million. With the progress in highly integrated electronics, more and more of the readout electronic is going to be integrated very close to the front-end. The design of the electromagnetic calorimeter by the CALICE collaboration [66] or by a North-American consortium [67, 68] has the silicon readout pads integrated into a readout board which sits in between the absorber plates. A special chip reads out a number of pads. A 12-bit ADC is included on the chip, and data are then sent on thin Kapton tape cables to the end of the module. There data from the different chips are concentrated, and sent on to the central data acquisition system. Such highly integrated detector designs have been successfully tested in large scale prototypes
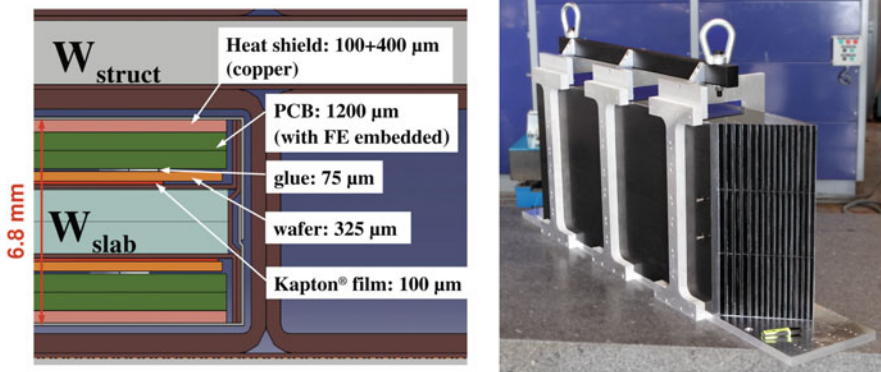
Fig. 22.15 Schematic figure of an integrated silicon-tungsten layer for an ILC ECAL (left) and tungsten absorber prototype (right) [37]

in test beams at CERN and Fermilab, although with a earlier version of the readout electronics, with a lesser degree of concentration (Fig. 22.15).

It is only with the progress in integration and in the resulting price reduction per channel that large scale Si-based calorimeter systems will become a possibility. Nevertheless the price for a large electromagnetic calorimeter of this type is still rather high, and will be one of the most expensive items in a detector for a linear collider. A cheaper alternative investigated is a more conventional sampling calorimeter readout by Scintillator strips. Two layers of strips at orthogonal orientation followed by a somewhat larger tile can be used to result in an effective granularity as small as 1×1 cm^2, nearly as good as in the case of the Si-W calorimeter. Light from the strips and tiles is detected from novel silicon based photo-detectors (for a more detailed description, see the section on hadronic calorimeters). The reconstruction of the spatial extent of a shower in such a system is more complicated, since ambiguities arise from the combination of the different layers. In addition the longitudinal information of the shower development is less detailed, but still superb compared to any existing device. This technology as well has been successfully tested in test beam experiments, and has shown its large potential.

Whether or not this technology or the more expensive Si-W technology is chosen for a particular detector depends on the anticipated physics case, and also the center-of-mass energy, at which the experiment will be performed. Simulation studies have shown that at moderate energies, below 250 GeV, both technologies perform nearly equally well, only at larger energies does the more granular solution gain an advantage. To some extent this advantage can be compensated by a larger detector in the case of the scintillator, though the price advantage then quickly disappears.

An extreme ansatz is a study trying to use vertex detector technology as readout planes in a calorimeter. The MAPS technology has been used to equip a tungsten absorber stack with sensors. This results in a extremely fine granular readout, where again only digital information is used—that is, only the number of pixels hit within

a certain volume is used, not any analogue information. This in turn means a much simpler readout electronics per channel, and a potentially more robust system against noise and other electrical problems. The amount of detail which can be reconstructed with such a system is staggering, and would open a whole new realm of shower reconstruction. However the cost at the moment is prohibitive, and many technical problems would need to be solved should such a system be used on a large scale [69].

22.6.6 Hadronic Calorimeters

In a particle flow based detector the distinction between an electromagnetic and a hadronic calorimeter conceptually disappears. Finely grained systems are needed to reconstruct the topology of the shower, both for electromagnetically and for hadronically interacting particles. Nevertheless, the optimization of the hadronic section of the calorimeter results in a coarser segmentation.

The traditional approach is based on a sampling calorimeter, typically with iron as absorber, maybe with lead, and with scintillators as active medium. New semiconductor photo detectors allow the individual readout of comparatively small scintillator tiles. These photo detectors are pixellated Si diodes, with of order 1000 diodes on an area of $1\,mm^2$. Each diode is operated in the limited Geiger mode, and the number of photons detected is read out by counting the number of pixels which have fired. This is another example of the previously discussed digital readout schemes. These so-called silicon photo multipliers (SiPM), also called Multi Pixel Photon Counters (MPPC), are small enough that they can be integrated into a calorimeter tile. To operate they only need to be provided with a potential of below 100 V, and the power lines are used to read out the signal from the counter. This makes for a rather simple system, which allows the instrumentation of a large number of tiles, and thus the construction of a highly granular scintillator based calorimeter. Complications which in the past severely limited the number of available channels—e.g., the routing of a large number of clear fibers from the tile to the photon counter, the operation of a larger number of bulky photo-multipliers of rather high voltage, etc all do not apply any more.

Light created through scintillation in the tile is collected by a Silicon photomultiplier, attached to each tile Earlier systems needed a wave-length shifting fibre, to adopt to the spectral sensitivity of the sensor (c.f. Fig. 22.16). A calibration of the energy response of the tile and SiPM system has two components: For small signals, the output signal shows contributions from one, two, three and more photons by clearly separate peaks in the amplitude spectrum. These can be used to establish the response of the system to single photons. At high signals, because of the limited number of pixels on the sensor, saturation leads to a non-linear response of the system. This needs to be measured and calibrated on the test bench, using a well calibrated photon source.
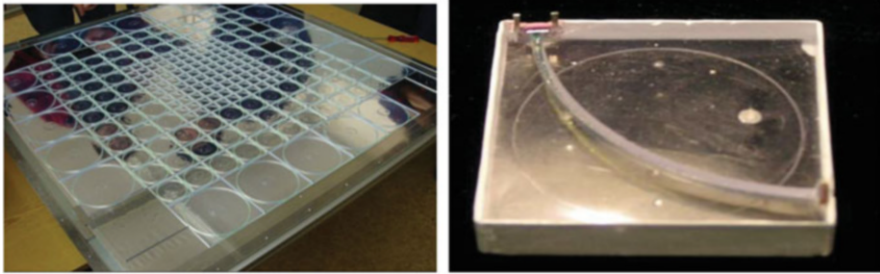
Fig. 22.16 Picture of a prototype readout plane for a highly segmented tile calorimeter (left) and one scintillator tile with wavelength shifting fibre and SiPM readout (right) [70]

The CALICE collaboration has designed a calorimeter based on this technology to be used in a detector at the linear collider. It is based on steel as absorber material, and uses $3 \times 3\,\mathrm{cm}^2$ scintillator tiles as sensitive elements. Each tile is readout by a silicon photomultiplier. A prototype readout plane is shown in Fig. 22.16. Groups of tiles are connected to a printed circuit board, which provides the voltage to the SiPM's, and routes the signals back to a central readout chip. This chip, which has been derived from the one developed for the Si-W calorimeter readout described in the previous section, digitises the signals, multiplexes them and sends them out to the data acquisition. Again, nearly all of the front-end electronics is integrated into this printed circuit board, and as such becomes part of the readout plane. This makes for a very compact design of the final calorimeter, with minimum dead space, and only a small number of external connections. This calorimeter has successfully passed a series of stringent beam tests in recent years, giving confidence that this technology is mature and can be used for a large scale detector application.

Recently the technology for SiPM advanced and pushed the sensitivity into the ultra-violet range, making a direct coupling between scintillator and silicon sensor possible (c.f. Fig. 22.17). The SiPM-on-tile technology has been proposed for the upgrade of the CMS endcap calorimeter. This system will use many of the developments done for an ILC detector, and be the first large-scale real-life application of this technology in an experiment. Through significantly smaller in size than the anticipated linear collider experiment, it will be a major asset for the LC community. Figure 22.17 shows a prototype readout HCAL plane using the SiPM-on-tile technology.

A potentially very interesting development in this area is again a digital version of such a calorimeter [72]. If the tile size can be made small enough - for hadronic showers this means a few $1 \times 1\mathrm{mm}^2$—a digital readout becomes possible. Counting the number of tiles belonging to a shower gives a good estimate of the showers energy. However scintillator tiles are difficult to built and read out for sizes this small—a major problems is the coupling between the light and the photo detector— so that a gaseous option is considered for this digital approach. Resistive plate chambers offer a cheap and well tested possibility to instrument large areas. They
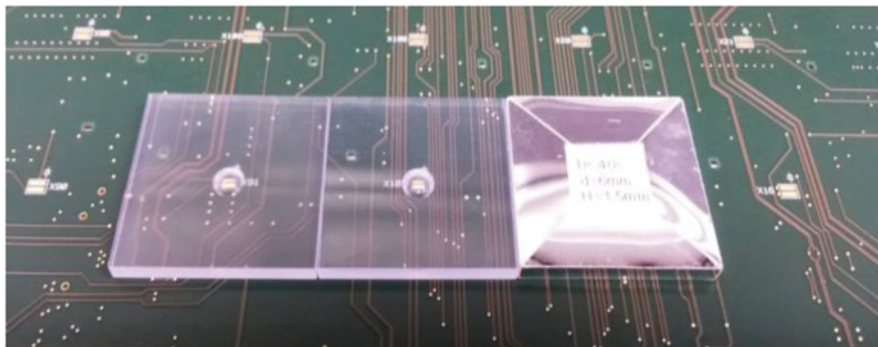
Fig. 22.17 Picture of HCAL scintillator tile with direct SiPM-on-tile readout [71]

are readout by segmented anode planes, which can be easily constructed with small pads of order of $1 \times 1\,cm^2$. The principle of such a digital calorimeter has been established, and seems to meet specifications [72]. A major challenge however is to produce readout electronics for the very large number of channels which is about an order of magnitude cheaper per channel than the one for the analogue tile technology.

An interesting compromise between digital and analogue readout calorimeters is the semi-digital approach. Here, moderately dimensioned cell sizes of $1 \times 1\,cm^2$ are combined with a rather simple 2-bit electronics with three signal thresholds. This would allow for having a high enough granularity to study the fine details of the hadronic shower evolutions and at the same time use the semi-digital charge signal for the analysis. A prototype semi-digital calorimeter for the ILD concept has been built and tested in beams and shows promising results [73].

A gaseous readout system has another feature which might be of advantage for a particle flow calorimeter. In the development of hadronic showers many neutrons are produced. Because of their long mean free path the loose energy and get absorbed far away from the core of the shower. This makes it very hard to attach these hits to the correct shower, thus creating a deficit in the energy for the shower, and creating fake hits away from the shower which might be confused with other nearby showers. Because of the very low cross section for neutrons in typical counter gases hardly any hits due to neutrons are recorded in a RPC based system. In a scintillator system, because of the high hydrogen and carbon content of the scintillator, the opposite is the case, and significant numbers if hits from neutrons are observed. On the other hand, neutrons travel slowly, and hits from neutron are later in time than other particle. Timing information at the 10 ns level might be good enough to reject a large number of the neutron hits in a shower. Its impact on the shower reconstruction is a subject of intense study at the moment, for both technologies, and no final verdict can be given which technology in the end has more advantages.

Large prototypes of ECAL and HCAL calorimeter systems have been built and tested in testbeam experiments. Figure 22.18 shows an event display for a combined
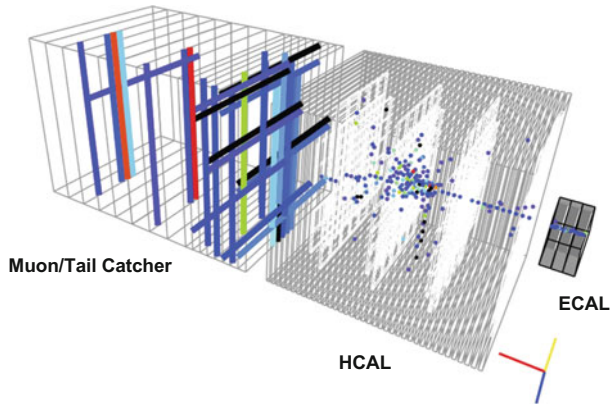
Muon/Tail Catcher

ECAL

HCAL

Fig. 22.18 Event in a combined testbeam where a 20 GeV pion (from the right) passes an ECAL prototype (small volume on the right), an analogue HCAL prototype with scintillator-tile readout (centre), and a muon system/tail catcher prototype with scintillator-strip readout (left) [71]

setup (from right to left) of a silicon-tungsten ECAL, an analogue scintillator-steel HCAL, and a muon/tailcatcher system with scintillator-strip readout (c.f. Sect. 22.6.7). A 20 GeV pion enters from the right, the details of the hadronic shower are clearly visible.

22.6.7 Muon Detectors

The flux return from the large field solenoids usually is realised as a thick iron return yoke. Often the iron is slit and detectors are integrated into the slots to serve as muon detectors. Many types of low-cost large-area charged particle detectors are possible and under investigation, e.g. resistive plate chambers, GEM chambers, or Scintillator based strip detectors. In a detector equipped with highly segmented calorimeters however a lot of the measurements traditionally done by such a muon system can be done in the calorimeters themselves. The identification of muons is greatly helped by the hadronic calorimeter, and its longitudinal sampling. Due to the high fields anticipated, muons below 3–4 GeV in fact never even reach the muon chambers, and need to be identified by the calorimeters together with the tracking system. The parameters of the muon are measured by the detector inside the coil, combining information from the tracker and the calorimeter. For these detector concepts the muon system in fact only plays a minor role, and can be used to backup and verify the performance of the calorimeter system.

An interesting approach is proposed by one of the ILC detector concepts [34]. Here the magnetic flux is returned not by an iron yoke, but by a second system of large coils. A smaller coil creates the high central field, of about 3 T, while a second larger coil creates a 1.5 T field in the opposite direction and serves as the flux return.

A system of planar coils in the endcap control the transition from the small to the large bore coil. In this concept muon chambers are mounted in between the two large solenoids. A similar approach is followed up in the studies for the very large detectors of potential very large hadron colliders.

22.6.8   Triggering at the ILC

The comparative cleanliness of events at the ILC allow for a radical change in philosophy compared to a detector at the LHC: the elimination of a traditional hardware based trigger. Triggering is a major concern at the LHC, and highly sophisticated and complex systems have been developed and built to reduce the very high event rate at the LHC to a manageable level [74, 75]. At the ILC with its clean events, without an underlying event, it is possible to operate the detector continuously and read out every bunch crossing. At a local level filtering is applied to the data to remove noise hits, and to eliminate as much as possible "bad hits", but overall no further data reduction is done. Events are written to the output stream unfiltered, and are only classified by software at a later stage. This allows the detector to be totally unbiased to any type of new physics, and to record events with the best possible efficiency. As a draw back the expected data rates are rather large. Great care has to be taken that the detector systems are robust and not dominated by noise, so that the data volume remains manageable, and the readout can keep up with the incoming data rate.

A slightly different approach has been suggested by the LHC experiments ALICE and LHCb, where upgrade plans foreseen to read out every event and to perform event selection and reconstruction in on-line processor farms.

22.7   Summary

Even though with the four LHC experiments, major experimental facilities recently built and commissioned, work on the next generation of experiments is proceeding. In particular the proposed linear collider poses very different and complementary challenges for a detector, with a strong emphasis on precision and details of the reconstruction. Significant work is happening worldwide on the preparation of technologies for this project. First results from test beam experiments show that many of performance goals are reachable or have already been reached. The move to ever increasing number of readout channels, with smaller and smaller feature sizes, has triggered a systematic investigation of "digital" detectors, where for a huge number of pixels only very little information per pixel is processed and stored. Whether or not such systems are really feasible in a large scale experiment is not proven yet. Tests over the next few years will answer many of these questions.

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