Chapter 12

R&D for the Future

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12.1 The LHC and Beyond

The discovery of the Higgs (BEH) boson [Box 8.2] in 2012 at CERN revealed the cornerstone of the so-called Standard Model (SM) in particle physics, a consistent description of the fundamental constituents of matter and their interactions [Box 6.4]. While the SM represents a spectacular synthesis, it is manifestly an incomplete description. It does not offer an understanding of the cosmic dark matter or the dark energy, supposed to fuel the expansion of the universe. It fails to provide a complete explanation of the apparent matter-antimatter asymmetry in the universe. These are some of the key questions that shape the research agenda in particle physics, astrophysics and cosmology.

New physics phenomena beyond the SM (BSM) can be found “directly”, by producing and detecting new particles or by observing processes forbidden in the SM. It can also be revealed “indirectly”, e.g. at colliders, through accurate measurements of properties of known particles (couplings, decay branching ratios, etc.), especially of top quark and Higgs boson, if they deviate significantly from the SM predictions. The former case, the only one traditionally considered a “discovery”, is the major hope for the future, but Nature will decide. The latter would reveal that new physics is at work virtually [Box 5.1] and may give a hint of its mass scale, potentially much higher than the centre-of-mass energy (E_{CM}) of the colliding particles, and its identity. Both directions should be pursued as far as possible, calling for maximizing the available energy and the luminosity [Box 6.1] of the collider, to produce the heaviest particles and explore the rarest phenomena possible, see also Box 12.1. These goals motivate the worldwide R&D in cutting-edge technologies.

CERN focuses R&D on areas of its expertise, predominantly in accelerator and detector technology. Although R&D is being conducted at CERN in the field of low and intermediate energy and of neutrino physics, this chapter emphasizes

CERN's major R&D activities directed towards the high energy (HE) frontier concerning new very large circular and linear colliders. Other HE options, presently under discussion, may influence this programme, as new results emerge: these are also briefly mentioned.

Exploitation of the LHC is the first priority of the European particle physics community and of CERN. A vigorous effort is made to increase and exploit its integrated luminosity, planned to rise from the present 4 fb^{-1} obtained in the first year (2015) with protons at 6.5 TeV to a total of about 300 fb^{-1} at 7 TeV, the nominal LHC energy, by 2022. In parallel, a significant upgrade, called High Luminosity LHC (HL-LHC) is in preparation, which aims to achieve a total integrated luminosity of 3000 fb^{-1} in pp collisions [1] by the second half of the 2030s. With this substantially higher integrated luminosity the accuracy of measurements, e.g. the Higgs couplings to bosons and fermions, will be improved and the discovery reach, e.g. the search for Supersymmetry, extended [Box 7.2]. The successful ion-ion programme will also be continued.

At the heart of the HL-LHC project is the replacement of the current focusing magnets in the interaction regions, based on NbTi technology, with stronger magnets based on the better performing Nb₃Sn superconductor, to reduce the beam size at the collision points [Highlight 12.2]. This progressive development, initiated for fusion reactors, is also relevant for future hadron colliders. The beam intensity will also be increased. These measures will yield a peak luminosity of $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ [1], a five-fold increase over the present luminosity. The latter already is a far cry from the initially foreseen $10^{33} \text{ cm}^{-2}\text{s}^{-1}$ which was the aim until 1987. At that time, it was realized that new prospects in physics, in particular Higgs physics, needed a factor 10 more in luminosity, which, thanks to vigorous and sustained R&D programmes both in accelerator and detector sectors, is presently achieved and exploited.

The peak luminosity is limited by the energy deposition of the collision products in the superconducting quadrupoles next to the collision point. A further practical constraint is the number of inelastic interactions μ per bunch crossing due to limited capability of the detectors to unambiguously associate particles with a given interaction. It is mitigated by "levelling" of the luminosity: the interaction rate is reduced through a small separation of the beams at the interaction point; as the beams loose intensity, the separation of the beams is gradually reduced, such as to keep the luminosity constant. This procedure maximizes the integrated luminosity subject to the constraint on μ in the detectors. For example, the number of μ is close to 30 at the present nominal LHC luminosity of $1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ increasing to about 140 at $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ [1]. (This number μ ignores fluctuations.)

For the HL-LHC the detectors will have to be significantly improved. New levels of radiation hardness will be required. Tracking systems and parts of the calorimetry in the forward region will have to be replaced. Trigger and data acquisition systems will need major upgrades [Highlight 12.6]. Overall, the quality of the measurements will be increased in line with the new physics agenda.

The choice of new projects for the post-LHC era will depend on the findings of LHC and HL-LHC and potentially other experiments. Therefore, a multi-pronged R&D approach has been put in place to prepare for this later choice of the optimum facility. Currently, two main R&D directions are pursued at CERN, coordinated with the European physics community. One is a very high energy e^+e^- collider, the Compact Linear Collider (CLIC); the other is a very high energy proton collider, the so-called Future Circular Collider (FCC-hh), considered to be the next “discovery facility”.

The e^+e^- collider would complement LHC by offering high precision measurements, in particular those associated with the Higgs boson, which could hint and/or reveal physics phenomena at a higher energy scale. However, direct searches for new phenomena or particles would be limited by its relatively low E_{CM} , although its precision will allow indirect searches up to much higher energy.

For the study of e^+e^- collisions, linear colliders are being proposed to avoid the strong increase of synchrotron radiation of circular colliders. In linear colliders the beams are accelerated in two linear accelerators (linacs) pointing at each other, avoiding any bending of the trajectory and, thus, synchrotron radiation. The particle beams enter in collision once and are then disposed of.

Linear collider R&D concentrates on several issues. First, very high accelerating fields have to be achieved to obtain the high collision energy in a practical length of the collider. Second, high luminosity requires maximizing the number of colliding particles and squeezing the beam to very small transverse sizes at the collision point. A strong constraint is the maximum power which can be taken from the electric grid: efficient generation of RF power is mandatory to produce these high accelerating fields.

Two different approaches to linear colliders are currently being pursued. A worldwide collaboration is developing the Compact Linear Collider (CLIC) [2], which can be constructed and operated in energy stages reaching at the first stage 0.38 TeV, the optimum for Higgs and $t\bar{t}$ studies, and ultimately 3 TeV E_{CM} . Figure 1 shows a possible location close to the CERN site. In its final stage, each linac would be 21 km long with an overall length of the facility of 48 km. An alternative approach is the International Linear Collider (ILC), also being developed by a worldwide collaboration, including CERN, aiming at E_{CM} of 0.5 TeV with an option for 1 TeV [3].

Fig. 12.1. A possible location of CLIC in the Geneva area close to CERN [2].

CLIC is based on high-frequency normal-conducting accelerating structures in the main linac operating at 12 GHz and with high accelerating gradients, the target being 100 MV/m [Highlight 12.4]. This very high accelerating gradient is motivated by the goal of reaching very high collisions energies, while keeping the overall length of the collider within manageable bounds. The salient point of the design concept is the use of an electron drive beam to generate the RF power by passive devices instead of a plethora of klystrons with their power supplies, requiring considerable maintenance.

The ILC plans to use superconducting accelerating cavities operating in pulsed mode at 1.3 GHz. This offers an important advantage compared to CLIC. The beam pulses can be much longer, which makes the generation of the RF by conventional klystrons straightforward. Also the time between bunch crossings in the interaction point is much longer, about 370 ns, which eases the detector design. The main drawback with respect to CLIC is that the achievable accelerating gradient — the aim is 31.5 MV/m — is about a factor three lower. This imposes a practical limit on the length and hence the ultimate energy of the collider.

A different idea is to use plasma waves as the accelerating mechanism in the main linac instead of normal or superconducting accelerating RF structures. These waves can be generated either by an intense electron, proton or laser pulse in a

gas-filled volume. The pulse will separate electrons and positively charged ions in the gas generating a strong accelerating electric field. A test of this novel acceleration method using a proton pulse is under preparation at CERN [4].

The detector designs for e^+e^- linear colliders are addressed by a worldwide R&D programme [Highlight 12.5]. The emphasis on precision measurements requires extreme performance of the detectors, concerning e.g. momentum resolution, jet energy resolution and impact parameter accuracy at the vertex to identify short-lived particles. This needs detectors with fine granularity and high resolution in space and time for the reconstruction of the individual secondary particles generated in an event and for background rejection. Vertex and tracking detectors have to be designed with low-mass materials to minimize scattering and loss of particles. The radiation levels are orders of magnitudes lower than for LHC, facilitating the use of new and more performing sensors, electronic and integration technologies. However, the detector designs have to take into account the specific machine-dependent backgrounds due to the extremely high fields produced in the collision of such tiny beams. Furthermore, an excellent coverage of forward emitted $e^\pm$ is mandatory, since they provide the best measurement of luminosity. The studies consider mainly two different concepts of detectors distinguished by the tracking instrumentation: a Time Projection Chamber or all-silicon sensors; both concepts put the accent on vertex detectors and very fine-grained calorimetry. The different time structures of the collisions in CLIC and ILC lead to specific requirements and features in the detector design.

Considering future proton-proton colliders, the option to equip the LHC with new dipole magnets capable of producing at least twice the field has received quite some attention; called HE-LHC it would offer collisions at twice the centre-of-mass energy, and possibly up to 33 TeV [5]. However, to make a large step into uncharted territory a very large hadron collider seems to be the tool of choice. Thus, in the CERN tradition of planning far ahead into the future, a study of a Future Circular Collider (FCC-hh) providing hadron collisions with E_{CM} at 100 TeV has been initiated. The design luminosity of $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ is similar to that of HL-LHC, with a possible increase to about $2 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$. This collider would have a seven-fold higher energy reach than the LHC, a step equivalent to that from the collider preceding the LHC, the US Tevatron, to the LHC. The production cross-sections of particles increase by large factors, e.g. more than 15 for the 125 GeV Higgs production. The search for a possible substructure inside quarks could be extended down to distance scales of 10^{-21} m [6].

FCC-hh [7] would take advantage of the technologies developed for the HL-LHC, but these technologies would be pushed beyond their present limits and new ones must be developed. The proton-proton E_{CM} is determined by the product of

the radius of the machine and the magnetic field of the dipoles that bend the beam. To achieve 100 TeV FCC-hh will use a tunnel that is about 4 times longer than that of the LHC (about 100 km vs. 27 km) and dipole magnets of about 16 T, i.e. twice the field of the LHC dipoles. A possible location of FCC is shown in Fig. 2. It is close to the LHC which would become the injector, following the well-established CERN practice of re-using the latest flag-ship accelerator as injector for the next generation.

The magnets are based on the same Nb_3Sn technology used for the HL-LHC but pushed to higher performance. Their development is the core technological challenge for the project. In addition, new superconductors that can operate at higher temperatures are being developed for the use as superconducting links between magnets and their power supplies, as are high-temperature superconductors (HTS) for use in insert coils to boost field [Highlight 12.3]. Having the potential to be used for coils that provide better performance than Nb_3Sn coils, this could pave the way to magnets with fields of 20 T and more.

Fig. 12.2. A possible location of FCC near CERN.

At this very high energy even protons start to emit a significant amount of synchrotron radiation. This is on the one hand beneficial since the size of the circulating proton beam will shrink with time increasing the integrated luminosity. On the other hand the magnets need to be protected efficiently from radiation that could heat them to levels exceeding the critical temperature for superconductivity. A novel beam screen design is being developed to cope with this issue.

The kinetic energy of each circulating beam is about 8 GJ, enough to melt 40 t of copper, about an order of magnitude larger than in HL-LHC. This can lead to critical situations, particular during beam injection or extraction from the machine, causing sometimes fractional beam loss. Higher demands are also placed on the collimation system, which removes unwanted tails of the circulating beam and protects the accelerator against accidental loss. A robust active and passive machine protection system must be developed.

The main requirements for the detectors come first from the energies of the particles produced. For tracking, one considers increasing the momentum resolution by about the same factor seven as the energy increase compared to LHC. This will require increased position resolution of the tracker and higher magnetic fields. Coverage of the very forward region, down to 2° polar angle for tracking and to 0.3° for jet detection, is planned. Calorimeters must contain fully the most energetic showers, hence be 12 interaction lengths deep, and must be precise at the 1–2% level. Moreover, all detectors need very high granularity to cope with the high level of interactions “piling up” at each beam crossing and to decipher the internal structure of jets, when these are actually the signature of very energetic particles, such as top quark, W, Z, and Higgs. The existing LHC detectors (Chapter 8) provide a good model for extrapolation, in particular when considering the magnetic structure to be adopted, and identifying potential “showstoppers”.

In each experiment the colliding beams will produce high event rates due to the high luminosity concurrently with a high rate of background events, which will produce collision products of up to about 500 kW per experiment. They will be emitted mainly close to the beam direction, so the focusing magnets near the detector need to be carefully protected.

The performance of a high luminosity e^+e^- collider (LEP3) replacing LHC in its tunnel and serving as a “Higgs-factory” has been evaluated [8]. Should a 100 km long tunnel be constructed for FCC-hh, it could be used for a powerful lepton collider either before (similar to the sequence LEP to LHC) or after FCC-hh. This option, FCC-ee [9], could provide high luminosity electron-positron collisions up to E_{CM} of about 350 GeV, albeit far below the energies of CLIC it would allow a similar physics programme as ILC [3]. The circular collider has the important advantage over the linear colliders that several experiments can be

installed for simultaneous data taking; in a linear collider two detectors could be considered but only one detector can be operational for data taking at any one time.

The energy of FCC-ee is limited by beam physics rather than by technology, which is well understood. The principal difficulty of the FCC-ee is achieving a luminosity of the order of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ at the highest energies. The intensity of the circulating beams is limited by the power due to synchrotron radiation losses. As this power per particle increases with E_{cm}^4 , the number of circulating particles has to decrease with energy to avoid excessive RF power consumption. The colliding beams need, therefore, to be very dense to produce sufficient luminosity. This leads to important intra- and inter-beam collision effects, which cause particle loss reducing the beam lifetime. The collider design must limit the inter-beam losses, which increase with luminosity and number of collision points.

The beam injection would differ from that of LEP, where the beam was injected at low energy and accelerated in the collider ring up to the collision energy. In FCC-ee, plagued by short beam lifetime, it is foreseen to have a booster ring in the same tunnel as the collider, by-passing the detectors. The beam is injected at low energy into this ring and accelerated to collision energy. Then it is injected into the collider ring on top of the already circulating beam. This practically continuous top-up injection has been previously used in smaller e^+e^- colliders and storage rings operating as light sources.

A study group, pursuing similar conceptual studies as done for an e-p option with LHC [10], is also considering the merit and feasibility of e-p collisions in FCC. In both cases, a recirculating linac would provide 60 GeV electrons for collisions with the protons in a single interaction point.

CERN is also attentive to other opportunities, such as, for example, the international programmes in neutrino physics, for which it provides R&D support, and has not lost sight of a Higgs factory based on a muon collider, having attractive features but requiring exceptionally challenging R&D.

Whatever the final LHC results, future accelerators will arguably play an instrumental role in the understanding of particle physics. CERN, conscious of the long lead time between concept and operation of large facilities, assumes a leading role in the international R&D collaborations preparing the HL-LHC, CLIC and FCC, while contributing in parallel to ILC. The future LHC results will tell us which of the facilities under study will be the optimum choice. CERN's multi-pronged R&D programme will put it in a position to be among the proponents of the next facility, hopefully a machine that opens a new energy frontier, or, if not, a factory focusing on the most relevant energy domains.

Physics prospects through the crystal ball**Box 12.1**

“Particle physics is at the most exciting crossroads in its history” [1]. The Higgs boson, the first spin 0 (seemingly non-composite) elementary particle, with its associated scalar field, is new to fundamental physics. Its self-coupling (SC) is a key property. The SM does not predict its mass and its low value is “unnatural” [Boxes 7.2 and 5.1]: one can therefore expect new physics at not too high an energy scale, making it “natural”. Will such a scenario, such as SUSY, extra dimensions, etc., appear in LHC Run 2, or elsewhere? If so, more luminosity — HL-LHC, and/or energy — HE-LHC and FCC-hh, will allow its detailed study. At HL-LHC, besides possibly discovering what the first phase of LHC did not reveal, a major effort will be put into improving the measurement of the properties of the top quark and Higgs boson. But open issues will remain, calling for much higher energy.

FCC-hh 100 TeV is not just “a quantitative upgrade of the LHC”. It would explore fundamental issues, probe distance scales down to 10^{-21} m, produce ~ 10 times heavier masses and much higher rates of basic processes. Accumulating 20 ab^{-1} ($1 \text{ ab} = 10^{-42} \text{ cm}^2$) would lead to $\sim 10^{10}$ Higgs bosons, 400 times more $t\bar{t}H$ events than HL-LHC, and $\sim 10^{12}$ $t\bar{t}$ pairs. FCC-hh will study the Higgs sector and its dynamics, with key inputs to its top coupling and to its self-coupling, the latter measured with $\sim 5\%$ accuracy, probing the shape of the Higgs potential around the vacuum of the Universe. Beyond the SM Higgs sector, Higgs exotic decays, such as μ -e, could be sought, as well as new states produced through the “Higgs portal”, connecting the SM world to one possibly hidden. For *dark matter*, the TeV sector of weakly interacting particles (WIMPs), from SUSY [Box 7.2] or any theory offering a lightest stable candidate, would be probed very well. FCC-hh would also allow precise measurements of di-lepton final states, for example, in search of heavy W' , Z' , i.e. new forces, and explore uncoloured physics (less evident because only subject to the electroweak force) at the TeV-scale.

For CLIC [2] and FCC-ee [3], the former benefits from higher E_{CM} , the latter from running simultaneously ≥ 2 experiments, and much higher L when used as a Z and W factory. With ILC, there could be a similar program at $E_{\text{CM}} = 350 \text{ GeV}$, measuring very precisely top and Higgs properties, reaching, from Higgs radiated off a Z boson, $\sim 0.2\%$ uncertainty on its coupling to Z and on its invisible decay branching ratio (see the FCC studies). At higher E_{CM} , $t\bar{t}H$ events would offer an accurate Higgs to top coupling measurement and W^+W^- fusion events would give access to rarer Higgs decay modes. CLIC at 3 TeV would deliver Higgs SC with 16% to 12% precision. Overall its decay width will be known at the sub-% level. With their clean environment and well-known initial state, the e^+e^- machines could search for BSM physics in two ways: (a) direct pair production of new particles up to $m = E_{\text{CM}}/2$, relevant example for SUSY partners of leptons and gauge bosons — a difficult topic at hadron colliders, and (b) indirectly, from precise SM measurements, sensitive to much higher masses and scales.

An e - p collider would focus on a more restricted domain of physics. A Higgs factory muon collider would allow the direct production of the boson in $\mu^+ \mu^-$ collisions.

[1] arXiv:1511.06495, arXiv:1606.09408 [2] arXiv:1202.5940 [3] arXiv:1601.06640

12.2 Accelerator Magnets with Ever-Higher Fields

Lucio Rossi

In 2008, with the LHC installation and initial commissioning finished, the CERN Magnet group started an R&D programme on high field magnets for the next generation of accelerators [11]. Its main scope is to develop advanced technology based on the use of Nb_3Sn superconductor. Nb_3Sn is not an alloy like Nb-Ti, which is relatively easy to handle and has to date been the superconductor of choice for use in accelerators (Tevatron, HERA, RHIC and LHC), it is a compound, capable of much higher performance with the potential to reach fields of almost twice the level of Nb-Ti. However, Nb_3Sn poses formidable challenges, the most severe being that it must be formed via a solid-state reaction, which requires heat treatment at 650°C in a controlled atmosphere and lasting many days, making it extremely brittle. This means it cannot be wound into a coil after reaction and every coil component must withstand such temperatures. In particular, the insulation cannot be organic (it would be converted into carbon) and the entire coil structure, composed of various materials, must cope with thermal excursion of almost 1000°C , from 650°C down to -270°C . The aim is to reach a critical current density [Box 4.3] of 1500 A/mm^2 at a field of 14–15 T (for Nb-Ti such current density is only achieved in fields of up to 7–8 T), while meeting the quality of accelerator magnets — implying uniformity of performance and small effective diameter of the superconducting filaments. Small filaments are necessary to avoid remanent fields at low field when the beam is injected [12]. The cross-section of a strand (an assembly of superconducting filaments embedded in a copper matrix) that is being developed in collaboration with a supplier of material for cables for the LHC upgrade is shown in Fig. 12.3. Also shown is a newly developed cable assembled from these strands; the white insulation sleeve is a braid of glass-fibre having a very low organic content to limit decomposition at high temperature.

Fig. 12.3. Left: cross-section of a superconducting strand (photo Bruker). Right: cable, showing the braided glass-fibre insulation.

In the present R&D phase, CERN is using simple flat racetrack coils, 400 mm long, which require a relatively small quantity of Nb₃Sn superconductor and have a short construction time, in order to assess conductor properties and coil technology representative of conditions occurring in a full-size magnet.

To develop a suitable conductor is obviously essential, but the mechanical structure of the magnet also requires attention. In the quadrupoles that will squeeze the beam at the interaction points for the LHC upgrade project for higher luminosity (HL-LHC), the field on the conductor will be 50% greater than in the present system, and forces and stresses on the windings will increase by more than a factor of two [13]. To cope with these stresses, CERN and collaborating laboratories (LBNL, FNAL and BNL in the US, CEA-Saclay in Europe, and others) are exploring new concepts for the coil layout and support structure. To date magnets were designed and manufactured according to the classical cos θ and Roman arch concept described in Chapter 4, using locking collars to provide pre-stress, but applying this approach to very high field magnets can lead to an unacceptable accumulation of stress. An innovative concept devised a few years ago at LBNL [14], in which the pre-stress is applied by pressurizing thin-walled components called bladders, is being perfected for the Nb₃Sn magnets of HL-LHC (Fig. 12.4). In this approach controlled pre-stress is applied directly to the coil support structure, rather than applying calculated pre-stress indirectly via the geometry of the assembly (as done for magnets from the Tevatron to the LHC). When the pre-stress is correct, calibrated keys are inserted to block any movement and the bladder pressure is released. With its 150 mm free bore and 12 T peak field the 7 m long quadrupole magnet will be the most powerful accelerator magnet of its type ever constructed.

Fig. 12.4. Cross-section of the MQXF Nb₃Sn quadrupole for the LHC upgrade (courtesy CERN-US-LARP collaboration).

The difficulties are even greater for the main dipoles being considered for a Future Circular Collider (FCC) [5], which calls for doubling the LHC field level and entails an increase of a factor four on the forces exerted on the coils. The field required for the FCC is in the region of 15–20 T. It should still be possible to reach the lower end of this range using Nb₃Sn, but the electromagnetic forces become so high that it may be necessary to review the layout of the coil. Detailed analysis and experiments are under way to find and test solutions, and a large test magnet, designed to provide a 13 T dipole transverse field in a 100 mm free bore, and incorporating both bladder-and-key support and racetrack coils with bent up ends, is now nearing completion.

Even more ambitious is the development of a new type of magnet to produce a pure dipole field, wound with the HTS material REBCO [Box 8.4] exploiting the large critical current of these HTS at low temperature in the presence of a strong magnetic field. The objectives are to develop (i) a practical high current flat cable [15], and (ii) a winding geometry where the cable is placed with its broad face parallel to the direction of the magnetic field, in order to minimize the adverse effects of critical current anisotropy in REBCO tape [16]. The initial goal, in 2017, is to generate a 5 T dipole field of a quality suitable for an accelerator; the final aim is to have both a demonstrator cable and winding structure that would open the way to building such a magnet for the 20 T range.

12.3 Teasing Performance from Superconductors Old and New

Amalia Ballarino

Low temperature superconductors (LTS) for use in high magnetic fields

For the FCC, or a possible energy upgrade of the present LHC, it is foreseen to use dipoles with an operating field of up to 16 T for bending the beam around the quasi-circular orbit. The LHC squeezes the most out of standard Nb-Ti material by cooling it to 1.9 K [Highlight 8.2], but because of an intrinsic upper critical field limitation Nb-Ti is not suitable for use in fields greater than 10 T, even when cooled down to 1.9 K (Fig. 12.5) [17]. Magnets for HL-LHC [13] and the FCC are therefore based on the use of the alternative LTS material, Nb₃Sn.

Current density at high field is crucial. For high field solenoids, and large devices such as ITER, space is available, and a critical current density (J_c) in the superconductor of 500–800 A/mm² at 12 T is comfortably sufficient, but this would lead to unwieldy accelerator magnets. The target J_c for the Nb₃Sn conductor

Fig. 12.5. The relative merits of various superconductors at 4.5 K (at 1.9 K for Nb-Ti) for use in high field accelerator magnets. The signs B// and B $\perp$ denote magnetic field direction parallel to and perpendicular to the broad face of the tape [17].

of the FCC is 1500 A/mm² at 16 T corresponding to an engineering critical current density (J_e), i.e. including stabilizing material and insulation, of about 500 A/mm².

Present material performance is sufficient for the HL-LHC magnets [18], but the desired target represents an improvement of about 50% with respect to the state-of-the-art, and sets an extremely challenging goal for the associated R&D.

For an application such as the FCC we would need a large quantity (several thousand tons) of high performance yet affordable material, clearly more than could be produced by one or two companies. Moreover it is expected that the FCC being studied would surely have to be built by a worldwide collaboration of institutes and industry. With this in mind, collaboration agreements have been set up between CERN and industrial partners in Europe and elsewhere to develop the required high performance material, as well as to foster interest in the project.

High temperature superconductors (HTS) used at low temperature

It is apparent in Fig. 12.5 that when used at low temperature HTS materials display far better characteristics at high magnetic field than Nb₃Sn [17]. While one type of BSCCO (Bi Sr Ca Cu oxide) material, BSCCO-2212, can be made in the form of multi-filamentary wire [19], which can be cabled, like Nb-Ti and Nb₃Sn, into convenient, fully-transposed^a flat (Rutherford) cables, it is also brittle when heat treated to become superconducting. As with Nb₃Sn, coils must be wound prior to

^aPersistent currents flowing in loops of superconductor give rise to unwanted multipole components of field and reduce transport-current capacity. Persistent currents are minimized by dividing the superconductor in the strands into thin filaments, twisting, and transposing strands within the cable.

Fig. 12.6. Sketch showing the build-up of a typical REBCO tape [20]. (Courtesy SuperPower.)

reaction (at about 900°C in a high-pressure, oxygen-rich atmosphere) — even more stringent conditions for magnet building than with Nb₃Sn. Besides being weak mechanically, the silver matrix of the material is expensive, so industry is pinning its hopes on so-called “2nd generation” REBCO (rare earth barium copper oxide) as being the most likely HTS material to find widespread practical applications.

REBCO superconductor (the rare earth is usually yttrium) consists of a 1–3 μm thick layer of material deposited on an inert substrate with several thin texturing buffer layers (Fig. 12.6) [20]. Several promising techniques have been adopted by industry for depositing the thin films of HTS onto the metal template, typically a 30–50 μm thick stainless steel alloy. A significant enhancement of the in-field performance is obtained via the creation of artificial pinning centres, by nano-engineering the defect structure in the REBCO film. Electrical stabilization is provided by copper plating one or both sides. Experimental inserts have been made to enhance the field of LTS solenoids from 20 T to 30 T, but for the dipoles and quadrupoles of an accelerator there are two major challenges: how to produce high current cables of the material, and how to reduce its cost. The small dipole insert winding referred to above uses cable derived from the Roebel bar concept (RACC) [15] to reduce magnetization effects (Fig. 12.7). An alternative topology, having the complete transposition of flat Rutherford cable, and which could also lead to better current sharing between strands (RERC), is being studied at CERN [21].

The cost issue will probably not be settled until there appears a regular large-scale commercial application. Although the cost of the raw material is low, the present ball-park price of 30 \$/m (for a standard 4 mm wide tape) barely covers manufacturing cost. For superconductors a more relevant cost-to-performance indicator is expressed in \$/kA m, so improving performance helps to reduce cost. However, for a substantial improvement a large-scale application is still needed: it is recalled that the accelerator community benefited from the low cost of Nb-Ti

Fig. 12.7. Left: sketch of a Roebel bar, originally conceived (in 1912) to reduce losses in electrical generators by dividing a solid bar into transposed parallel bars. Top right: the concept applied to REBCO tape [15]. Lower right: a tape cable with the topology of flat Rutherford cable [21].

thanks to demand for MRI magnets. Use of the materials in *high magnetic field* is presently a niche application, requiring kilos of material: for a future collider many tons would be needed. At present it is the *high temperature* performance of HTS material that is most appreciated, as liquid nitrogen can be used as the coolant (thanks to increasingly efficient and powerful cryo-coolers, cooling with liquid hydrogen, liquid neon or helium gas is also gaining interest). With this in mind, CERN has been investigating applications that would be useful for accelerators, but could possibly lead to wider use and external demand for the material, and enable a decrease in its cost due to economies of scale.

HTS links for powering superconducting circuits

In view of the success of the development for the LHC of low-loss current leads using HTS [Highlight 8.4], it was decided to look for other possible applications of the new materials to accelerator technology. The proposal of using superconductors for power transmission dates back to seminal work done in 1967 [22], but the advent of HTS saw a regain of interest as it offered the possibility of using liquid nitrogen for cooling. In superconducting accelerators the circuits for powering the magnets require long lengths of interconnecting cable, for which use of the new materials is attractive. The requirement is more exacting than conventional power transmission — several circuits with quasi-DC currents operating at up to 20 kA, instead of single- or 3-phase cables carrying 2 to 4 kA — but the presence of a cryogenic system for the accelerator facilitates the cooling. A study was therefore launched at CERN to evaluate the potential [23], which was later seized upon for HL-LHC [24], where superconducting links would allow relocation of power converters and sensitive electronics to radiation-free areas.

Several types of cable have been studied, and demonstration units built and evaluated [25]. One type (designed to feed twenty-four 600 A circuits) consists of a twisted pair based on the use of standard 4 mm wide tape of BSCCO-2223 (as used for the current leads), REBCO, and magnesium diboride (MgB_2) tape. MgB_2 has a critical temperature of 39 K, is potentially low cost, and is attractive for use in applications where magnetic fields do not exceed 4 T to 5 T. Besides minimizing electrical coupling, the twisting provides sufficient flexibility to allow safe bending within the minimum bending radius (1 m) of the cryostat. This type of cable was new, and cabling machines were developed at CERN to assemble and splice pre-reacted materials. Such cables have been successfully made and tested.

A second type of cable is being developed for the high current circuits. Tens of cables operating at different currents (ranging from 0.12 kA to 18 kA) are contained in the same compact cryogenic envelope with a total current-carrying capacity of over 150 kA. For cooling, the cryogenic system can provide helium gas maintained at below 25 K. Besides the cost aspect, this is interesting because unlike BSCCO 2223 and REBCO, MgB_2 can be made in the form of a round multi-filamentary wire, convenient for making large cables. In 2008 a programme was launched by CERN to focus on the development of round MgB_2 superconductor. A collaborative R&D activity was set up with a manufacturer [25] to develop wire having a critical current of 320 A at 25 K and 0.5 T, and a minimum bending radius of 100 mm, suitable for the development of high-current cables. The first attempts to make MgB_2 wire were based on the architecture of a tape product [26]. After several iterations and the measurement of many samples, the study finally converged on a 1 mm diameter strand that satisfied the electrical and mechanical requirements. The baseline topology of the multi-circuit cable is illustrated in Fig. 12.8. The space taken by the group of cables including its cryostat is less than a quarter of that required for water-cooled bus-bars.

Fig. 12.8. The build-up of the multi-circuit cable proposed for efficient cold powering of the magnet system of the high luminosity upgrade of the LHC. The twisted strands consist of 30 superconducting filaments of MgB_2 embedded in a Monel matrix, copper plated for stabilization and ease of splicing.

A 40 m long MgB₂ cable, assembled at CERN, has been successfully tested at up to 20 kA @ 25 K [27], with a peak field on the conductor of 0.9 T.

The activity on superconducting links was performed in the interest of accelerator technology, but such cables can be used in any application requiring the transport of large currents. In fact, the 20 kA prototype tested at CERN also served as a demonstrator for a project proposed for long-distance power transmission [28]. This aspect of the activity was covered in the framework of a collaboration between CERN and the Institute for Advanced Sustainability Studies in Potsdam [29]. Such a cable could also be interesting for application to a pipetron-type accelerator [30], being considered for the injector of FCC-hh, and for FCC-ee [31].

12.4 RF Power for CLIC: Acceleration by Deceleration

Igor Syratcev

The Compact Linear Collider (CLIC) [2] is based on a two-beam scheme. RF power at 12 GHz for acceleration is produced by decelerating a high-intensity but relatively low-energy 2.5 GeV electron beam, the **drive beam**. The **main beam** to be collided with the opposite beam is accelerated with a field of 100 MV/m.

The linac of the main beam is operated in a pulsed mode; every 20 ms each accelerating structure will be fed with a ~250 ns pulse of RF power that generates the accelerating field, with a total peak RF power per burst and linac of about 4.5 TW. During the pulse, a train of 312 bunches, spaced by only 0.5 ns, is accelerated. This burst mode operation is essential to limit the losses of RF power in the accelerating structures, the main issue being the cost- and power-efficient generation of the RF pulses.

The novel design concept uses an electron drive beam to generate the RF power. For each main linac pulse, a long (140 μ s), high-current drive beam pulse of 2.4 GeV is produced in a central injector complex for each linac. It is accelerated using long 1 GHz RF pulses that can be produced efficiently with klystrons. During the pulse, the total klystron power is about 10 GW. The design of the drive beam accelerating structures allows to transfer close to 100% of the power to the beam. The long beam pulse, which has a spacing between bunches of 60 cm, is then sent into a system of combiner rings. Here groups of 24 sequential 250 ns long parts of the drive beam pulse are merged to form a single 250 ns long drive beam pulse with only 2.5 cm bunch spacing which are then sent into one decelerator that runs in parallel to the main beam. This decelerator consists of a sequence of Power Extraction and Transfer Structures (PETS) in which most of the beam kinetic energy is turned into RF power. In this concept the initial pulse

is compressed in time by almost three orders of magnitude and its peak power increased by the same factor. The concept has been demonstrated in a test facility at CERN [2].

To reach the luminosity needed for physics, the colliding CLIC beams will have a vertical size of only 1 nm, i.e. about ten times the size of a hydrogen atom! At this scale, the natural motion of the ground would displace the beams enough to jeopardize the collision. To avoid this, all of the beam guiding magnets are decoupled from the ground with a novel local feedback system. It consists of inertial sensors, which measure the magnet motion, and of piezo-movers, which can compensate the ground motion. Prototypes of this system manage to stabilize heavy objects to within 0.1 nm. The machine components must be placed with an accuracy of order 10 μm , about an order of magnitude better than the 100 μm typically achieved with the alignment systems used in existing accelerators. A novel alignment system has therefore been developed and successfully tested.

Two key elements are described hereafter: the PETS-structure producing the RF power with the drive beam and the accelerating structure providing the accelerating field for the main beam.

Power-Extraction and Transfer Structure (PETS)

This passive device has to produce 136 MW peak RF power at 12 GHz in 250 ns feeding two accelerating structures of the main linac by decelerating the drive beam (Fig. 12.9).

Fig. 12.9. RF powering scheme of CLIC showing the PETS in the drive beam and the accelerating structures of the main beam [2].

The pulse length is longer than the bunch train length in the main beam as the first part of the pulse serves to build up the field in the accelerating structure.

Since the drive beam energy becomes relatively low during deceleration, it is rather sensitive to perturbations, in particular to harmful parasitic higher-mode electro-magnetic fields (HOM) induced by the head of the beam pulse and acting adversely on the tail of the beam pulse by transversely deflecting it. Thus, the design must assure strong damping of these modes.

The structure chosen is a periodically loaded waveguide with 34 cells and 0.21 m active length. It is formed by eight vanes carrying a cog-rail being the outer cell boundary as shown in Fig. 12.10 [2]. Each of the cells is 6.25 mm long with a corrugation depth of 4.28 mm. The electron beam travels in the centre of this structure, generating the RF power in the interaction with vanes of the device. The length of a cell corresponds to one quarter of the 12 GHz RF wavelength.

The vanes are joined by electron-beam welding and separated by 2.2 mm wide longitudinal slots which distort the field pattern of the HOM such that their energy is mainly stored in these slots. A lossy dielectric material close to the slot opening guides the HOM energy to the damping material in the enlargements filled with absorbing silicon carbide. The design keeps the surface field to less than 56 MV/m.

In addition, the operation of the individual PETS has to be controllable either to significantly limit field build-up in case the PETS suffers from breakdowns or to cut power to an accelerating structure broken down. To condition either structure a gradual increase of the power level is also required. These features are guaranteed by a remotely controlled variable reflector in the waveguide after the PETS output coupler terminating the structure [32]. A total of 35 832 PETSs form the RF power generator for each of the 1.5 TeV beams.

Fig. 12.10. Left: model of PETS showing the octants and the slots leading to the enlargements for the absorber (the absorbent material is not shown). Right: view of an octant.

Accelerating structure

Each accelerating structure consists of an array of 26 copper cells (Fig. 12.11), basically pill-box cavities [Box 3.1], with an eigenfrequency of 12 GHz [33]. The array is preceded by the input coupler which links it to the waveguide coming from the PETS. The RF power is transmitted from cell to cell through the iris. The RF pulse starts before the main beam pulse arrives in order to build up the electric field in all cells and lasts during the beam pulse to replace the energy picked up by the beam (travelling-wave structure).

The final structure parameters including the frequency are the result of an optimization procedure striking a compromise between performance, power consumption and cost. To this end millions of variants were simulated based on a model of investment and exploitation cost as well as taking into account the results from a long series of model testing under RF power [33]. Simply stated, high-frequencies are favoured as this limits the stored energy in the structures leading in turn to their small dimensions.

The resulting cell design maximizes the accelerating field and minimizes high-power RF effects such as RF breakdown (rate $<10^{-7}$ per pulse and per m) and RF induced surface heating (<45 K). Further, it combats the development of HOM, equally harmful in the main linac.

The cell of 80 mm external diameter has a geometry minimizing surface fields (<230 MV/m). The four radial damping waveguides departing from the inner effective accelerating cell are terminated with broad-band loads (not shown) made of silicon carbide to suppress the perturbing HOM without affecting the fundamental mode (12 GHz). The iris radius and thickness are tapered along the structure to provide a constant accelerating gradient, which avoids hot spots along the structure. Their average values are 2.75 mm and 1.34 mm, respectively.

Fig. 12.11. One of 26 cells of the accelerating structure showing the central opening, the iris and the radial waveguides connecting to absorbers of higher modes.

The cell geometry is adapted to the manufacturing process. One side of the cell carries all the features required for the RF, whereas the other side is flat for bonding (Fig. 12.11). The cells are diamond machined, joined by diffusion bonding under hydrogen at about 1000°C and vacuum baked at 650°C. With exacting machining tolerances, typically in the 1 μm range, the tuning of the final structure is avoided.

A number of test facilities is in operation worldwide including those at CERN which houses the only facility modelling the two-beam scheme in addition to a number of test stands powered by klystrons for high turn-around of testing structure variants. Nominal accelerating gradients of 100 MV/m have been achieved in the accelerating structures under development in a worldwide collaboration with the required low break-down rate while the PETs have been tested at the nominal output power of 150 MW. However, more variants of these two structures have to be built and examined to address HOM damping, lifetime, breakdown statistics, industrial-scale fabrication, and better understanding of the break-down mechanisms.

12.5 The Next Energy Frontier e^+e^- Collider: Innovation in Detectors

Lucie Linssen

Throughout the history of particle physics, both protons and electrons, with their respective antiparticles, have been used extensively for high energy colliders [Box 4.1]. The merits and difficulties of physics research with high luminosity proton–proton colliders are briefly described in the Box 8.3.

Electrons, in contrast to protons, are genuine elementary particles. Apart from initial-state radiation and beamstrahlung effects (see below), they provide very good knowledge of the initial state of the collision. The e^+e^- annihilation cross section (Fig. 12.12) decreases as E^{-2} and, at TeV energies, cross sections for most processes are small, typically of order 10^{-37} cm^2 or lower, and at a similar level as the interesting events in proton–proton collisions. However, the absence of the large physics background that plagues hadron colliders allows for much easier signal selection. If they can deliver sufficiently high luminosity ($>10^{34} \text{ cm}^{-2}\text{s}^{-1}$), future e^+e^- colliders are therefore the tool of choice for precision measurements.

Two design studies of high energy, high luminosity e^+e^- colliders are currently hosted by CERN. The Compact Linear Collider (CLIC) is designed to cover a centre-of-mass energy range from $\sim 350 \text{ GeV}$ to 3 TeV, while the e^+e^- option of the large circular collider, FCC-ee, is foreseen to cover energies from the Z-pole

Fig. 12.12. Calculated e^+e^- cross-sections.

at ~ 91 GeV up to the top pair production threshold near 350 GeV. CERN also participates in the International Linear Collider (ILC) study, a 250–500 GeV collider, upgradable to 1 TeV, which could be realized in Japan.

Beyond their respective *physics discovery potential*, all three machines will allow high-precision measurement of processes involving known particles. Besides a deeper understanding of the underlying processes these studies could provide insight into the nature of new physics at very high energy scales. In this context the most prominent examples are the accurate measurement of the Higgs boson and its couplings to mass, as well as the mass and production characteristics of the top quark. In the case of FCC-ee this is complemented by measurement of W and Z bosons with very high statistics. The centre-of-mass energy at CLIC will give access to the discovery and accurate measurement of pair-produced particles with a mass of up to 1.5 TeV, or single particles up to 3 TeV. In this context new electroweak particles or dark matter candidates are of special interest, as they may escape detection at the LHC. In addition, CLIC energies will give optimal access to double Higgs production, governed by the Higgs potential.

Spin plays a key role in research at an e^+e^- collider. In particular, beam polarization gives access to the spin dependence of the production processes. A polarized e^- beam at a linear collider would be useful for testing the Standard Model (Chapter 7) and “feeling” new physics. While waiting for a broader view on the physics case after LHC, the CLIC baseline design foresees e^- polarization, and reserves space in the design for the more challenging e^+ polarization option.

The superb accuracy potential offered by e^+e^- collisions drives the *detector requirements* [34–36]. Several “must-do” physics measurements, serving as benchmarks, determine specifications for the momentum resolution, energy measurement and quark flavour tagging of the detectors. The vertex and tracking systems have to be significantly more accurate (a factor 3 to 5) than the current state-of-the-art LHC systems, while highly granular calorimeters are needed to obtain the anticipated improvement of a factor 1.5 to 2 in jet energy resolution. In order to achieve this performance, the tracking and calorimeter systems will be located inside a powerful superconducting solenoid (Fig. 12.13).

The detectors also have to meet requirements driven by the *beam conditions*. In a linear collider the transverse size of the bunch is very small — indispensable for achieving high luminosity (12.1 and 12.4). As a result, the electron and positron beams produce strong electromagnetic radiation (beamstrahlung) in the high field of the opposite beam. Such radiative effects change the centre-of-mass energy distribution of the e^+e^- collisions: the electron or positron may radiate a high-energy photon before the collision, resulting in a centre-of-mass energy below the nominal value. As a result, the spectrum of centre-of-mass energies shows a sharp peak at the nominal value and a long tails towards lower energies. This so-called luminosity spectrum can be measured in situ from Bhabha scattering, and subsequently used in the interpretation of the physics results. In principle the tail allows for a crude exploration of the physics which lies below the nominal energy, but with much reduced luminosity.

Fig. 12.13. Artist view of a possible CLIC detector.

Beamstrahlung is also a source of additional background in the detectors, which is strongest at CLIC due to its high beam energy and smaller beam size. Background e^+e^- pairs are produced at high rates and very close to the beam direction, while background hadrons with transverse momenta up to ~ 5 GeV/c reach out to larger polar angles. At 3 TeV the pile-up of beamstrahlung over the entire 156 ns bunch train amounts to ~ 5000 charged particles and ~ 19 TeV of energy deposited in the central detector volume. For comparison, at most one hard e^+e^- physics event is produced per bunch train at 3 TeV. Provided the CLIC detectors produce timing information for all hits, with an accuracy of 10 ns for the tracking detectors and 1 ns for calorimeter hits, these beam-induced backgrounds can be suppressed efficiently in the data. At the ILC, beam-induced backgrounds will be less pronounced, due to the lower centre-of-mass energy and larger bunch sizes. Moreover, individual bunch crossings will be separated by several hundred ns. Therefore, the ILC detectors do not need to provide such accurate time information. Reduced occupancies in the inner ILC detector regions will allow the most inner vertex layer to be placed at a radius of 15 mm, as compared to 31 mm for the 3 TeV CLIC. At FCC-ee the dominant backgrounds originate from synchrotron radiation in the bending magnets closest to the experiment. The extent of this background and the resulting demands on the detector are under study.

Given the small e^+e^- interaction cross sections the radiation levels are low. For example, at CLIC they will be typically a factor 10^4 lower than at LHC. Only the small very-forward calorimeter systems will experience LHC-like radiation levels.

In the domain of *vertex and tracking detectors*, semiconductor devices provide the best accuracy. Silicon detectors are extensively used at the LHC and many interesting developments are on-going for the upgrades of the LHC experiments, with special emphasis on reducing the mass of the detectors and increasing their granularity, position accuracy and radiation hardness. Requirements for CLIC push the demands on position accuracy, cell size and low mass even further. For example, at CLIC each layer of the vertex detector should feature a position resolution of 3 μm and a time resolution of 10 ns for a material thickness corresponding to 0.2% of a radiation length X_0 . Cell sizes need to be smaller than $25 \times 25 \mu\text{m}^2$ to limit occupancies due to beam-induced background particles. Assuming a minimal amount of material required for supports and services, the design allows for 50 μm sensor thickness and 50 μm readout ASIC thickness. To reduce heat dissipation, the electrical power to electronics will be turned off during most of the 20 ms interval between 156 ns bunch trains. This allows for air cooling, thereby avoiding the material otherwise needed for cooling tubes and liquids.

The semiconductor industry progresses fast, thanks to societal applications such as personal computers, mobile phones, sensors and cameras. Even though

particle physics has often quite specific detector requirements, innovations in the wider realm of semiconductors provides many opportunities for our field to progress. An example is the decreasing CMOS feature size with the associated increase in density of readout electronics. Industrial sensor and camera R&D involves integrated (high-resistivity) sensor materials, nanostructures and compact interconnect features, which are also interesting for particle detectors. The current readout ASIC for CLIC is based on 65 nm CMOS technology. Compared to the 0.25 μm CMOS circuits commonly used at LHC, this technology can accommodate about 25 times more logic cells per mm^2 , which is very similar to the ratio of LHC to CLIC pixel sizes in the vertex detector. The 65 nm technology has the added advantage of reduced power consumption, with reduced detector mass as a further bonus.

CLIC R&D is also testing so-called integrated HV-CMOS sensors, which comprise a high resistivity sensor layer (for fast signal development) and the electronics circuit in the same thin device [37]. At the current stage of the R&D, the integrated sensor includes two amplification stages. As a result, the detected signal is large enough to be transmitted through a simple layer of non-conductive glue (AC coupling) to the readout ASIC (Fig. 12.14).

At a readout pitch of 25 μm this represents a significant production gain over the delicate traditional bump-bonding (DC coupling) between sensors and readout ASICs. The ALICE experiment is currently developing a related fully-integrated monolithic CMOS technology for their 10 m^2 inner tracker upgrade. It has supreme position resolution, albeit with limited signal speed [38]. In the coming years one can expect such trends in technology to evolve further, and tenacious particle physicists to cleverly exploit such features for their future detector systems. The CLIC R&D effort towards a fast and thin 100 m^2 e^+e^- silicon tracker system with 7 micron single-point resolution and small readout cells will surely explore such opportunities.

For the *calorimeter system* CLIC will make use of the so-called *Particle-Flow Analysis* (PFA) approach, a development that was initiated at CERN by the ALEPH experiment at LEP and was successfully developed further for the CMS experiment at the LHC [39]. The approach will be exploited in future experiments thanks to newly available detector technologies.

Traditionally, the reconstruction of collision data proceeds mostly independently for the tracker system and the calorimeter. The production angle and momentum of charged particles are measured in the tracker, while the energy of nearly all outgoing particles (except neutrinos and muons) is measured independently in the calorimeter system. Particle showers in the calorimeter, in particular in the hadron calorimeter, develop over large volumes. This hampers the

Fig. 12.14. AC-coupled assembly of an integrated HV-CMOS sensor (CCPDv3 PAD) and a CLICpix readout ASIC in 65 nm technology with $25 \times 25 \mu\text{m}^2$ pixels. The HV-CMOS sensor includes two amplification stages. The AC coupling is achieved through a thin layer of non-conductive glue.

matching between tracking and calorimeter information when particles are produced close in space. Quark and gluon jets are typically composed of many nearby particles, 60% of which are charged hadrons, 30% are photons (mostly from π^0 decays), and 10% are neutral hadrons. The charged hadrons are normally measured to high accuracy in the tracker (relative accuracy better than $10^{-4} p_T$, with p_T in GeV/c). The energy of photons is measured typically better than $15\%/\sqrt{E}$ (with E in GeV) in the first layers of the calorimeter system. Neutral hadrons are not equally well measured, due to the much larger fluctuations in the hadronic shower development. Using the best information available for each of the individual particles in the jet, the jet energy resolution can be improved by a factor 1.5 to 2 compared to traditional calorimeter-only reconstruction techniques. This will allow to reach $\sim 3.5\%$ accuracy in jet energy measurements at high energies and to separate W, Z and Higgs decays reliably in multi-jet topologies.

This detailed PFA can be realized by combining fine-grained calorimetry with powerful event reconstruction software. In case calorimeter cells are small enough, one can assign energy deposits to individual particles in the event reconstruction. At the same time, PFA allows to identify individual particles originating from beamstrahlung and to reject them in the data analysis by using time information [40]. Figure 12.15 shows the PFA reconstruction of a simulated event in the CLIC detector model.

Cell sizes in the active layers are foreseen to be as small as $5 \times 5 \text{ mm}^2$ in the electromagnetic section of the calorimeter and some $3 \times 3 \text{ cm}^2$ in the hadronic section. The electromagnetic section is foreseen to have 30 layers in depth of one radiation length each, while the hadronic section will have ~ 60 layers for a total of 7.5 interaction lengths in order to fulfil the jet energy resolution goals up to 3 TeV centre-of-mass energy. Compared to the current ATLAS or CMS calorimeters this represents a factor 400 increase in the number of readout cells.

Fig. 12.15. PFA reconstruction of a simulated event in the CLIC detector model. The various colours are used to distinguish different reconstructed objects in the crowded regions.

SiPMs are single photon counting devices composed of an array of avalanche photodiodes (APD) on a common silicon substrate. The miniature devices can host over 10 000 APDs per mm^2 , and are insensitive to magnetic fields. Compared to traditional photomultipliers they offer a wealth of new possibilities for particle detection, including highly granular calorimetry.

Prototypes of highly granular calorimeters have been pioneered by the CALICE collaboration, initially targeting calorimetry for the ILC and subsequently also for CLIC and other facilities. Full-size fine-grained electromagnetic and hadronic calorimeters were built and successfully tested. Several options for the active layers and passive absorbers were explored [41]. Such fine-grained prototypes do not only demonstrate technical feasibility and performance capabilities, they also provide invaluable information on calorimetric shower development: a very welcome input for detector simulation tools, such as Geant4.

The demanding performance goals for future e^+e^- collider experiments have motivated advanced detector R&D across the planet. The community is preparing to realize these experiments in a foreseeable future and to explore the physics discovery potential at these new machines.

12.6 Hadron Collider Detectors: A Bright and Energetic Future

Werner Riegler

The LHC programme is at present planned to extend to about 2035. Until 2025 the collider will operate at the nominal parameters, followed by the implementation of the so-called High Luminosity LHC (HL-LHC), which should increase the delivered luminosity by another factor of 10 at the same energy [1].

The LHC represents a 7-fold energy increase over previous colliders. The first phase of the LHC is presently clearly focused on its *discovery potential*. Whatever the outcome of searches for new physics may be, the second phase guarantees a programme characterized by *precision measurements*. As one example, the couplings of the Higgs boson, discovered in the first phase, will be measured to high precision with the high statistics sample from the HL-LHC.

The major upgrades of the general purpose detectors ATLAS and CMS aim at optimizing their potential for both aspects. For HL-LHC they will implement technologies to perform these precision measurements at a luminosity of $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ corresponding to close to 4 billion collisions/s, and which must remain operational at unprecedented levels of radiation. The aim of the ongoing R&D is to achieve a detector performance at these increased rates that is at least comparable to, if not better than, the present one [42, 43].

The improvement programmes of the ALICE and LHCb experiments also focus on increased rate capability and measurement precision. They are however not linked directly to the HL-LHC and follow therefore a different time line [44, 45].

The requirements for the LHC detector upgrades are clearly defined: the R&D is targeted at radiation resistance, rate capability, very low-mass sensors for precision tracking and new technologies to implement sophisticated trigger algorithms in computing farms.

Beyond the LHC, detector concepts for a large circular hadron collider with collision energies of about 100 TeV are being developed. More than ever before will the long-term improvements in detector performance be linked to progress in technology of semiconductors, computing and networking. Given the continued close to exponential growth of performance of these technologies, they arguably will be a major contributor to the required detector improvements and strategic changes in experimentation.

Some examples from this long term programme are presented here.

ATLAS and CMS at HL-LHC

For the HL-LHC, the luminosity will be increased from the nominal *peak* value of 10^{34} to a *constant value* of $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. At this luminosity an average of 140

inelastic proton–proton collisions are produced every 25 ns at the centre of the detector. The vertices of these 140 proton collisions are spread out along the beam direction with an average separation at the millimetre level and time differences on the scale of 10 ps. Given the time response of present tracking sensors these collisions are therefore *simultaneous*, dubbed *pile-up* in the jargon of the experimenters. The individual collision vertices have to be disentangled with high granularity pixel detectors. However, R&D on sensors reaching timing resolutions in the 20 ps range targets temporal separation of the collisions. Cherenkov detectors, calorimeters with fast readout or silicon sensors with internal charge amplification have the potential to reach such levels of time resolution, the challenge being to cover a large area, where necessary.

The pixel sensors close to the beam pipe will experience radiation loads in excess of 10^{16} hadrons/cm² during their lifetime, a factor ten above present day levels. Novel sensor materials and geometries, operated at low temperature will be required to withstand these radiation levels. High quality positively doped silicon material is becoming available, in which the so called n-in-p technology can be implemented and should provide the required radiation resistance.

ATLAS and CMS will replace their entire trackers [Highlight 8.7] for HL-LHC operation in order to cope with the increased rate of particle production as well as to satisfy radiation requirements. They also plan to extend the tracking acceptance to very small forward angles to measure forward jets, signatures of the fundamental “vector boson fusion” processes, i.e. the collision of two (virtual) bosons emitted by the incoming partons on both sides.

The 40 MHz event rate has to be reduced to a manageable 1 MHz detector readout rate. Muon and calorimeter information alone is not sufficient for efficient event filtering, so tracking information must be included to achieve the required selectivity. CMS will use closely spaced silicon sensors which will provide angular and hence momentum information on track segments. High momentum tracks can be selected in the trigger decision to achieve the required selectivity.

The liquid argon calorimetry of ATLAS is well adapted for the high radiation levels of the HL-LHC. It will mainly require electronics upgrades to cope with higher rates. The forward crystal calorimeter of CMS will however not withstand the HL-LHC radiation load. It will be replaced by a high granularity sampling calorimeter with Si-detector readout. Such high granularity calorimeters are required to exploit the *Particle Flow Techniques* (PFA), a novel method for event reconstruction [Highlight 12.5]. Jet energies are measured with the calorimeter combined with the momentum information of the charged particles provided by the high precision tracker. The calorimeters are also used for particle identification and measurement of the neutral component of the jet. In the high pile-up

environment of HL-LHC sufficiently high granularity is essential for the proper matching of tracks with the calorimeter energy clusters.

The most extensive part of the detector upgrade concerns the readout electronics. The already quoted close to exponential performance increase of microelectronics, expected to still continue in the near future (“Moore’s law”), has a dramatic impact on the strategy for treatment of detector signals, event selection (trigger), data readout and data storage. While e.g. the signals of the ATLAS liquid argon calorimeter are presently buffered in an analogue pipeline and only digitized upon a trigger at a maximum rate of 100 kHz, the expected decrease in ADC power consumption will allow 10 bit digitization at the full bunch crossing rate of 40 MHz by the time of the HL-LHC.

The present readout of the ATLAS and CMS detectors is based on a first level hardware trigger from calorimeters and the muon system, reducing the 40 MHz bunch-crossing rate to a 100 kHz detector event readout rate into a so called High Level Trigger (HLT) computing farm, which performs further event selection, resulting in an event rate of about 100 Hz to permanent storage. For the HL-LHC, an HLT input rate of 1 MHz, corresponding to 5 Terabyte/s (TB/s), and an event storage rate of 10 kHz are considered, shifting a more refined and flexible event selection and larger data samples to offline analysis computer farms.

Reading the full event rate of 200 TB/s into a computing farm without any hardware trigger selection would be not economic, but technically feasible in the near future. The major principle obstacle is the transmission of the electric signals from the sensors over some meters of copper or aluminium cable to the optical conversion electronics for transmission over fibre. The large quantity of metal cables and the cooling infrastructure to remove the heat from the power-hungry high-rate transmission links in the active volume of the tracker impact severely its performance. Therefore efficient data reduction on the detector electronics, radiation hard optical links and low power signal transmission are key to a fully continuous readout of future detectors.

ALICE, LHCb

Towards the end of 2020, ALICE and LHCb will implement important upgrades to prepare the experiments for the HL-LHC era. These experiments will realize dreams that have been keeping the detector community awake for quite a time.

Given the increase in processing power and network performance, ALICE and LHCb plan to no longer rely on *hardware triggers* to reduce the events rate. All events will be transferred at data rates of 1 to 4 TB/s into a computing farm for detailed online event reconstruction. In the case of LHCb the online farm will perform event selection, while in ALICE, the online farm will perform data

reconstruction and compression with all events written to permanent storage. Evidently this approach exploits at best the physics potential provided by the LHC.

The ALICE detector is optimized for heavy ion collisions. A requirement of its research programme is to measure very low momentum particles. This implies an ultra-low mass silicon tracker to limit the degradation of measurement precision due to the deflection, i.e. multiple scattering, of particles [Box 3.2]. This will be achieved by developing novel CMOS monolithic silicon sensors. In current silicon detectors, the sensors and the readout electronics are separate components that must be connected by sophisticated soldering techniques. The monolithic sensors used for ALICE integrate the sensor diode and signal processing circuitry inside the pixel on the same silicon substrate. The total thickness can therefore be reduced to 50 μm , compared to the several hundred μm typical of present Si trackers. Together with low mass carbon fibre support structures and aluminium signal buses, a significant reduction in mass can be achieved, improving measurement precision by a factor of 3 over the presently used silicon tracker.

Detection efficiency of >99%, and radiation resistance up to 10^{13} hadron/cm² have been achieved on prototypes, well adapted for the heavy ion collision rates of ALICE. The ALICE tracker will use 10 m² and 12.5 Gpixels of this revolutionary integrated detector + signal processing technology [44].

The Time Projection Chamber (TPC) [Box 4.5] of ALICE will implement a novel readout technology that transforms the detector from a so-called “gated” into a continuously sensitive mode of operation. The standard operation of a TPC using wire chambers requires a gating grid to be closed for a time of typically a few hundred microseconds after each event. This prevents the ions, created in the gas amplification on the sense wires, from moving back into the drift volume and building up significant amounts of charge. However, this limits the readout-rate capability of the ALICE TPC to about 3 kHz. This will be overcome by replacing the wire chambers with a stack of 4 specifically developed GEM detectors [Box 4.6]. Their design will prevent 99% of the ions from moving back into the TPC volume, so that the TPC can be continuously sensitive without the need for gating. These GEMs will measure the particle tracks with an accuracy of 200 μm . The 100 m² of GEM detectors will have 500 000 channels, with their signals continuously digitized at a rate of 5 MHz [44].

The LHCb experiment is focused on the physics of B-mesons and selects events based on the characteristic decay pattern of these particles, the so-called displaced vertices [Highlight 8.6]. In order to achieve this complex selection, the present detector was conceived for an average rate of only one proton collision per bunch crossing in the detector. The collaboration plans to increase this rate by a factor of 10. The new detector readout electronics will operate at the full bunch-

crossing rate of 40 MHz and transfer all data to a computer farm where it is possible to select the superimposed events. In addition to the electronics upgrade, some other detector systems will also have to be upgraded.

LHCb will employ a large scale scintillation fibre tracker. Exploiting the attractive features of a fibre tracker as a fast low mass detector has until recently been hampered by the difficulty of deploying a large number of photo sensors in a cost effective way. The recent development of Silicon Photo Multipliers (SiPM) having single photon detection efficiency has however changed this picture dramatically. The LHCb fibre tracker will use 12 detection layers with a total of 12 000 km of fibres and will employ 590 K SiPM channels [45].

The signals from the SiPMs are digitized and transferred to the online farm at the bunch crossing rate of 40MHz. The radiation damage of these SiPMs due to the total hadron fluence in excess of 10^{14} hadrons per cm^2 results in a significant increase of the SiPM dark count rate, and the detector is therefore operated at 233 K (minus 40°C) to mitigate this effect to acceptable levels.

Beyond LHC

One post-LHC collider concept is a 100 TeV circular hadron collider being considered in the Future Circular Collider (FCC) study [7]. This machine is again conceived as a *discovery machine* [Box 12.1]. The programme is to provide proton collisions at 100 TeV, initially with a luminosity of $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ at 25 ns bunch crossing and leading to an ultimate luminosity of $30 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ at 25 ns or 5 ns bunch crossing.

Radiation levels will increase in proportion to the luminosity. For example, a pixel detector at a radius of 2.2 cm from the beam will be exposed to a fluence of 5×10^{17} hadrons/ cm^2 , thirty times the already challenging HL-LHC numbers. Clearly, R&D for radiation hard sensors is again key for such an enterprise.

Most ideas about physics beyond the Standard Model are related to the Higgs boson, so Higgs studies can be seen as a portal to new physics and benchmark for a future collider. Due to its low mass, the Higgs particle will be boosted to very small forward angles at high collision energies, requiring an acceptance for precision tracking and calorimetry down to polar angles of 2° .

The present detector concepts consider solenoids of 4 to 6 T and 5 to 6 m free bore radius with forward dipoles or solenoids for momentum spectroscopy. In comparison, the CMS experiment uses a 4 T solenoid with a free bore radius of 3 m [Highlight 8.12]. An iron flux return would be exceedingly heavy ($\sim 10^5$ t), which has motivated seeking alternative solutions. Active shielding with a shielding coil, partial shielding with iron or completely unshielded geometries are presently being studied. A conceptual layout is shown in Fig. 12.16 [46].

Fig. 12.16. Cold mass of the twin solenoid and dipoles. In the figure the support structure is made partially transparent to reveal the superconductive coils. The outer diameter and total assembly length is 27 and 43 m, respectively [46].

To achieve a resolution of 10–15% for particles with a p_T of 10 TeV (10 times better than LHC) requires a tracker combining long distance of tracking, a large area and very high precision tracking. A prime goal is therefore to continue the development of monolithic silicon sensors into fast and radiation hard sensors that will allow high precision tracking over large areas at affordable cost.

The detector and accelerator studies for this energy frontier are part of the “Future Circular Collider (FCC)” study [7], a comprehensive conceptual design study for post-LHC particle accelerator options in a global context.

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