Chapter 8
Continuing the Story: Detectors for a Future Linear Collider ILC or a Future Circular Collider FCC

Beyond the **H**igh **L**uminosity **L**arge **H**adron **C**ollider HL-LHC, described in the previous chapter, the two main future colliders, currently under discussion are the next potential e^+e^- machines, the **I**nternational **L**inear **C**ollider ILC [320], briefly the **C**ompact **LI**near **C**ollider CLIC and the **F**uture **C**ircular **C**ollider FCC. The requirements of both colliders and possible detectors are significantly different but also some synergies exist. Figure 8.1 informs about the increase in size of detector systems over the past 40 – 60 years, plus the envisioned ones for the next two decades.

The logarithmic plot behaves Moore-like[1] so far but is flattening out in the near future. The field is very active. R&D, assembly efforts, quality control plus the related logistics increased a lot in the last years and will even further in the future. To construct a detector with a couple of people over the summer-break is no longer possible. Also R&D efforts today are quite diverse as a result of the many new possibilities and needs for the next generation of tracking detectors. Whole R&D-*only* collaborations exist, e.g. RD50 [336]. In Fig. 8.1, it can be noticed that the Tracker detectors are not getting larger neither for the High Luminosity LHC nor for the future planned linear collider. The future high granularity silicon calorimeters will take over, although surface areas of around 400 m^2 for the FCC tracker are being discussed these days.

The future will tell us where we will go next. In the next two sections some ideas, plans and current R&D activities will be discussed.

Compact Linear Collider – CLIC

In competition to the ILC, another e^+e^- machine up to 3 TeV with a different acceleration concept is proposed, namely the **C**ompact **LI**near **C**ollider CLIC. The CLIC detector concept is, in many ways, similar to the one of the ILC, described in the next section. The main difference or better additional challenge is high beam induced

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[1] According to Gordon E. Moore co-founder of Intel, the number of transistors placed on an integrated circuit increases exponentially, doubling approximately every 2 years. Published in 1965, Moore's law predicts the future of integrated circuits.

F. Hartmann, *Evolution of Silicon Sensor Technology in Particle Physics*,
Springer Tracts in Modern Physics 275, DOI 10.1007/978-3-319-64436-3_8

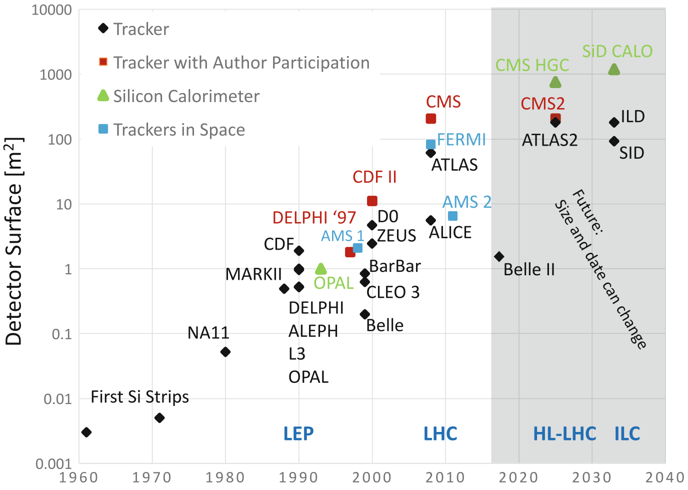

Fig. 8.1 Evolution of silicon detectors – area. In logarithmic scale the plot displays the increase in area for the last 40 – 60 years, the detectors approved and considered for the next decades. Plotting number of channels and power consumption would result in similar figures until the LHC era but will increase further for the future detectors

backgrounds (Beamstrahlung[2] due to the planned ultra-small bunch length/width (45 nm/1 nm/44 µm (σ_x / σ_y / σ_z)). These nanometer sized bunches are required to achieve high luminosity despite the relatively low repetition rate of 50 Hz (bunch trains). Typically only 1 hard interaction per bunch train is expected. The means to reduce this background is by time-tagging the physics events per strips/pixels better than 10 ns. The front-end readout therefore features the capability of **T**ime **o**f **A**rrival ToA and **T**ime **o**ver **T**hreshold ToT.

Sensor technologies for the vertex and tracking detector under discussion are

- Full monolithic HV-/HR-CMOS (rf. also Sect. 1.12.4, page 112).
- **C**apacitively **C**oupled **P**ixel **D**etector CCPD configuration (rf. also Sect. 1.12.4, page 112) glued to an ASIC
- **S**ilicon on **I**nsulator **S**o**I** technology with in-pixel signal processing (rf. also Sect. 1.12.3, page 109)
- Very thin planar sensors plus thin ASIC (50 µm sensor + 50 µm)

The collaboration is also working closely with the CALICE collaboration on a high granularity calorimeter. The reader is referred to [1, 152, 192, 275, 339] for more details.

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[2] From beam + bremsstrahlung – electromagnetic beam-beam interaction.

8.1 A Silicon Tracker for the International Linear Collider – ILC

A linear e^+e^- collider in the TeV centre-of-mass range[3] is considered to be the next ultimate challenge – the **I**nternational **L**inear **C**ollider ILC. The Technical Design Reports, with all details, can be found here [320]. At the current time, a lot of technical aspects about possible detector concepts is under ongoing discussion, meaning despite the TDR, choices can change depending on the ongoing developments and the final installation date. The one clear fact is as the instrument will be built for precision physics, all detector parameters are driven by physics channels need and resolution. The vertex detector must be able to tag b, c, τ decays and some people think about s quarks. The detector will be operated trigger-less, i.e. all collisions will be recorded. Detailed but very early proceedings about the vertex detector ideas are presented in [50, 218, 355], a first discussion about strip implementation in [86]. By comparing these with [271] and [320], evolution of design and detector solutions become clear while the original constraints and concepts are mostly still valid. The concept of "**p**article **f**low PF algorithm" is followed throughout the detector design, **every** particle must be reconstructed for optimum jet resolution. Therefore the tracker must be able to reconstruct **all** charged particles with high momentum resolution.

There were still four concepts in 2008, namely GLD (**G**lobal **L**arge **D**etector); LDC (**L**arge **D**etector **C**oncept); SiD (**Si**licon **D**etector) and the **4th Concept**. In 2009, the GLD and LDC merged into a single detector concept: the **I**nternational **L**arge **D**etector ILD [321].

Today (2017), there are two validated concepts and which have been selected by the International Detector Advisory Group IDAG in 2009: the ILD (vertex+Si strips+TPC[4]) and SiD (vertex+silicon strips).

SiD "**Si**licon **D**etector" will be an all-silicon detector similar to CMS consisting of an inner high precision vertex detector plus a tracker at higher radius. The vertex detector with 5 pixel barrel layers ranging from $R = 14$ to 60 mm plus 4 large (small stereo angle) forward disks plus pixelated 3 forward disks. The outer tracker then equips 5 barrel layers ranging from $R = 22$ to 122 cm plus 4 slightly tilted disks in forward direction.

The ILD will consist of an inner vertex detector (**S**ilicon **I**nner **T**racker SIT) with three high precision double-ladder layers $R = 16$ to 60 cm, a large TPC followed by an envelope Tracker at $R = 180$ cm as precision link towards the calorimeter (**S**ilicon **E**xternal **T**racker SET) in the central barrel as well as in the forward direction, plus a silicon forward detector (**f**orward **t**racker **d**etector FTD). The high-radius envelop[5] Tracker will consist of small pitch (50 μm) silicon strip sensors implementing the **P**itch **A**dapter PA as first or second metal routing in the sensor itself. Also the TPC

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[3] The accelerator is planned to have a centre-of-mass energy of 500 GeV with the option to upgrade later to 1 TeV.

[4] **T**ime **P**rojection **C**hamber TPC.

[5] Also called SET or Intermediate Silicon Layers.

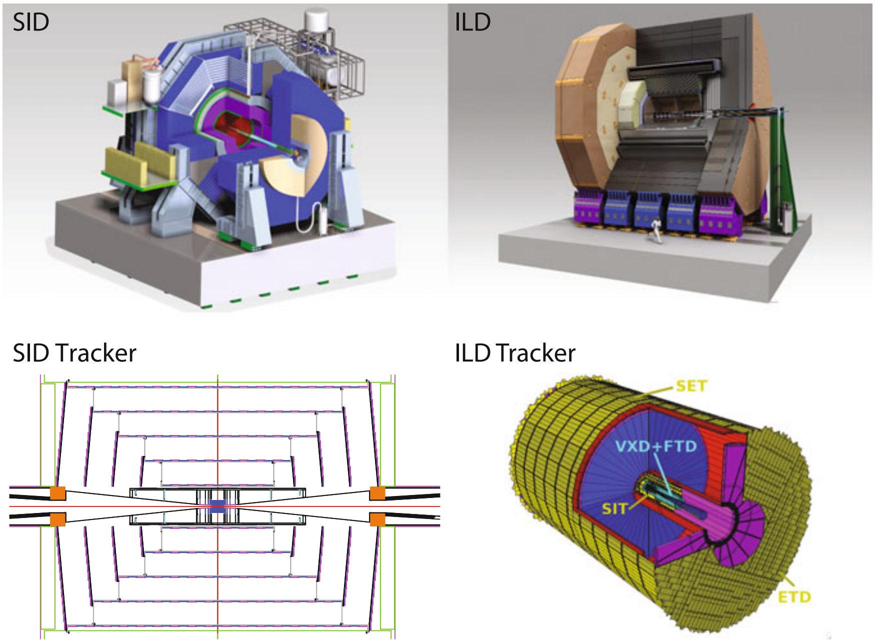

Fig. 8.2 The schematics of the two ILC detector concepts and their Trackers from [320]. The usual onion shell concept is being followed for both SiD and ILD: vertex – tracking – ECAL – HCAL – solenoid – muon chambers, for the barrel part as well as for the endcaps. The main difference between the detector concepts is the large TPC of the ILD detector. Interestingly, due to the large radius of the SET, the total silicon surface is even larger for the ILD

readout at the volume end will possibly be realized with silicon sensors or high-resolution gaseous chambers.

The solenoid due to its high mass will reside outside the Tracker and also outside the calorimeters for both concepts (5 T for SiD and 3.5 T for ILD), similar as for CMS.

Design studies and small prototypes exist for a silicon tungsten Si – W calorimeter[6] with $5 \cdot 5\,\mathrm{mm}^2$ cells and even a digital "tera-pixel" ECAL with $50 \cdot 50\,\mu\mathrm{m}^2$ MAPS readout.

The schematics of SID and ILD are displayed in Fig. 8.2.

In this section the current vertex detector requirements are discussed plus some promising sensor technology candidates. The future will tell which technology will be chosen.

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[6] Adapted concept will be used in CMS rf. Sect. 7.2.

The requirements are listed below:

- space point resolution of 3 – 4 μm or better for
  - $20 \cdot 20\ \mu\text{m}^2$ (or $25 \cdot 25\ \mu\text{m}^2$) pixels
- impact parameter resolution in Rz and $R\phi$:
  - $\sigma_{d_0} = (5\,\mu\text{m})^2 + (10\,\mu\text{m}/(p_T \sin^{3/2}\Theta))^2$
- a two-track resolution of 40 μm or better
- transverse momentum resolution: $\Delta(1/p_T) = 5 \cdot 10^{-5}/\text{GeV}$
- ultra-low material budget 0.1% X_0 radiation length per layer
  - low power consumption
  - gas flow cooling, crucial to allow low mass construction
  - very light structural elements, e.g. silicon carbon foams
- hermeticity with special focus on forward geometry
  - full coverage $|\cos\Theta| < 0.98$
- operation in magnetic field up to 5 T
- triggerless operation – particles come in bunch trains with a large gap in between
  - fast electronics
  - in situ storage
  - high granularity
  - fast sensor
- moderate radiation tolerance

Unlike a circular electron–positron collider with a constant time interval of beam crossings the ILC will operate with particle bunches organized in trains. In the planned configuration as of today [30] there will be five trains with 1312 bunches per second. The bunches are separated by 554 ns (baseline) summing to a total duration of 1 and 199 ms quiet time. Therefore fast electronics operating in power pulsed mode are necessary, especially with the need to consume very low power to run without active fluid cooling. The triggerless ILC operation together with the dense particle bunches and long trains poses the following requirements on the vertex detector: Detector response must be fast, occupancy must be low to avoid high pile-up and detectors must be either read out very fast (e.g. 20 times per train) or signals must be storable in the detector/readout cells. Without a trigger, all signals are read out, therefore sparsification is ultimately needed as well as a pixelated geometry for the vertex detector.

The possible candidates having been studied were numerous and included (1) **C**harge-**C**oupled **D**evices CCDs, CPCCD **C**olumn **P**arallel **CCD**s, (2) **M**onolithic **A**ctive **P**ixels **S**ensor MAPS based on CMOS technology, (3) **DE**pleted **P** channel **F**ield **E**ffect **T**ransistor DEPFETs, (4) **S**ilicon **o**n **I**nsulator SoI, (5) **I**mage **S**ensor with **I**n situ **S**torage (or **I**n-situ **S**torage **I**mage **S**ensor) ISIS,

(6) **H**ybrid **A**ctive **P**ixel **S**ensors HAPS and advanced 3D sensor-electronics integration concepts. The basic technologies are explained in Sect. 1.12 while the devices for the ILC come in several flavours with some specific implementations and also some technology combinations. Standard CCDs as used in digital cameras are not fast enough, proposed column parallel readout CPCCD helps or **S**hort **C**olumn **C**harge-**C**oupled **D**evice SCCCD, where a CCD layer and a CMOS readout layer is bump bonded together. Chronopixels are CMOS sensors, with the capability to store the bunch ID (time). ISIS sensors combine CCD and active pixel technology, a CCD-like storage cell together with CMOS readout implemented. Also **F**lexible **A**ctive **P**ixels FAPs integrate storage cells in the traditional MAP cells. **F**ine **P**ixel **CCD**s FPCCDs are under discussion to decrease occupancy. To summarize, the different varieties of CCDs, DEPFET, MAPS and SOI are designed to be read out every 50 μs, while ISIS and FAPS store signal in cell memory and will be read out in the 199 ms between trains. Also FPCCDs and chronopixels are designed for in-between train readout.

Given the recent success of **H**igh **V**oltage HV-CMOS and **H**igh **R**esistivity HR-CMOS, CMOS devices will certainly deploy a certain 'low' high voltage to deplete (or at least partially deplete) the thin sensors. In my personal humble opinion, the full monolithic CMOS concept with some 'low' high voltage would be the ideal candidate (rf. also Sect. 1.12.4).

In addition to all the above-discussed technology choices, the requirement to achieve a ultra-low mass tracker demands thin sensors. Methods are under investigation to either have thin epitaxial sensors like CCD and to thin the other devices. Edgeless processing is under investigation to allow near-adjacent sensor placement instead of traditional staggering; the particle flow algorithm would strongly suffer from non-instrumented regions.

While the above mentioned HV-CMOS technology can be considered baseline for the more outer tracking layers, the inner vertex layers are targeting an even more ambitious technology. New 3D integration technologies are under investigation where two or more thinned layers of semiconductor devices are interconnected to form a monolithic "chip" (see also Sect. 1.11.1, page 106). In early design concepts, the real sensor together with analogue, digital and even optical electronics are vertically integrated in a monolithic circuit. This concept has many obvious advantages and early prototypes are very promising.

The above-mentioned link layers (FTD) towards the TPC and especially the layer (SET) surrounding it and also the full silicon tracker (SiD tracker) might still be realized with the strip technology of today, but also here thinning of sensors is under discussion. Also long ladders had been investigated with "long" strips to stay within a reasonable number of readout channels. Avoiding standard hybrids at the end of modules, second metal routings were discussed with a bump bonding field even on strip sensors and chips with 512 or even 1024 channels were in planning in 2008 [86] and are now proven to work [320]. With the current advances in HV-/HR-CMOS, this might change.

The rich number of valid technological choices proves the liveliness of the silicon sensor development in the last years.

8.2 The Next Big Future Circular Collider – FCC

Preliminary studies have been started to discuss a 80 – 100 km ring accelerator with about 100 TeV centre-of-mass energy. 16 Tesla dipole magnets would be needed and technology seems in reach. The International **F**uture **C**ircular **C**ollider FCC collaboration consider CERN as hostlab for first studies but also China is studying/evaluating a similar endeavour (CepC/SppC study CAS-IHEP with 50 or 100 km circumference). The main emphasis defining the infrastructure requirements is a 100 TeV hadron-hadron collider (FCC-hh or HE-LHC), an e^+e^- collider (FCC-ee) in the same tunnel is studied as a potential intermediate step, a proton electron collider option (FCC-he) is studied as well. Also the instantaneous and integrated luminosities for the hadron collider are supposed to be very high (hypothesis) – peak baseline $\mathcal{L} = 5 \cdot 10^{34}$ and ultimate $30 \cdot 10^{34}$ as a later second step. This would lead to an integrated luminosity of $\mathcal{L} = 250$ or $1000\ \text{fb}^{-1}$ per year summing in 10 years to $\mathcal{L} = 2.5\ \text{ab}^{-1}$ and $15\ \text{ab}^{-1}$ in the next 15 years; thus totalling to about $20\ \text{ab}^{-1}$. In this case, detectors should be designed to last about $\mathcal{L} = 30\ \text{ab}^{-1}$. The ultimate peak luminosities correspond to about a pile-up of PU = 1000 with about 10 vertices per millimetre at 25 ns bunch crossing or PU = 200 for 5 ns bunch crossings.

This section is not meant to describe a specific detector design (FCC-hh case) but to collect the basic ingredients to do tracking of particles with transverse momentums in the tens of TeV range. Most numbers come from [256, 334].

To exploit such a machine, the detectors should feature

- a tracking resolution of about 15% at 10 TeV
- a precision tracking and calorimetry coverage up to $|\eta| = 4$
- tracking and calorimetry for jets up to $|\eta| = 6$
- b-tagging
- timing for pile-up mitigation

The need for high precision tracking in the forward region demands either a very long solenoid or a dipole magnet in the forward region. Since the magnet coils will be very large, an iron return yoke will be very costly and heavy, so geometries with a shielding coil or an unshielded solenoid are investigated. With such high integrated luminosities the requirements for the radiation tolerance is incredibly high. For $\mathcal{L} = 3000\ \text{fb}^{-1} = 3\ \text{ab}^{-1}$ at the HL-LHC we expect about $2 \cdot 10^{16}\ n_{1\text{MeV}}/\text{cm}^2$ for the innermost layer at about r = 3 cm with the increased inelastic cross-section at 100 TeV this translates to roughly about $4 \cdot 10^{16}\ n_{1\text{MeV}}/\text{cm}^2$ for $3\ \text{ab}^{-1}$ at the FCC or $4 \cdot 10^{17}\ n_{1\text{MeV}}/\text{cm}^2$ for the full lifetime corresponding to $30\ \text{ab}^{-1}$. Decreasing radius a bit further and/or adding a bit of error margin one arrives at the $1 \cdot 10^{18}\ n_{1\text{MeV}}/\text{cm}^2$ or 100 GRad level. We do not 'yet' have a radiation tolerant technology for these levels. This probably means we cannot instrument as low in radius as we are doing for the LHC but still, even the outermost Tracker radii will suffer about $1 \cdot 10^{16}\ n_{1\text{MeV}}/\text{cm}^2$.

Now, how can a 15% p_T resolution at 10 TeV be achieved? The FCC community is using TKLayout for first design studies (rf. Sect. 7.1 on page 293). The Glückstern formula (rf. [118]) plus the multiple scattering term gives the basic answer – see formula 8.1.

$$\frac{\sigma p_T}{p_T} = \frac{\sigma p_T}{p_T}_{|res} \otimes \frac{\sigma p_T}{p_T}_{|MS} = \sigma_x \frac{p_T}{0.3B \cdot L^2}\sqrt{\frac{720}{N+4}} \otimes \frac{0.0136}{0.3B \cdot L}\sqrt{\frac{x}{X_0}} \qquad (8.1)$$

with L lever arm $\sim$ full detector radius; B magnetic field in Tesla; N number of track layers,[7] σ_x point resolution, x/X_0 fractions of radiation lengths.

Clearly large $L \cdot B$ and small σ_x seems key, since it improves resolution. Having more layers helps but impacts adversely the multiple scattering. Unfortunately a high B at large radius is very difficult (high field energy). One of the layouts being discussed would even feature 2 solenoids (one around Tracker and calorimeters and a shielding one around the muon detectors) plus dipoles in the forward direction.

For example a Tracker with r = 2.5 m, a B-field of 6 T, 16 layers and 3% of a radiation length per layer would need a point resolution σ_x of about 20 µm. Decreasing the radius by a factor of two (CMS design) would mean decreasing σ_x and x/X_0 per layer by a factor of four. Of course increasing the B-field by a factor four would also do the trick, but this is probably technically not feasible. A σ_x of about 5 µm or even lower is however possible and given the very high pile-up, a full pixel detector is anyhow the only viable solution. x/X_0 of 0.75% seems doable as well, especially if monolithic technology would be used. For such a precision also the alignment needs to be perfect to even exploit the point resolution. For muons, the precision will be defined by the muon chambers with much larger L.

Tracking in very forward direction requires disks very very close to the beam pipe and for b-tagging also as close as possible to the interaction region, where barrel layers already occupy the space. LHCb, as forward spectrometer tracks up to $|\eta| = 5$. The CMS Upgrade will manage up to $|\eta| = 4$ but without b-tagging capability and without good momentum resolution due to weak 'effective' B-field. Can one realise a tilted layout to cover both needs?

To cope with the high pile-up probably also the calorimeter will be done the CALICE/HGC way, as fine granular imaging calorimeter with silicon-pad or even silicon-pixel detectors in-between absorber plates.

The amount of silicon surface of tracker plus calorimeter will be huge!

The super-stringent requirements require probably monolithic pixelated sensors having a very low material budget, a very fine granularity and excellent point resolution. $20 \cdot 20$ µm^2 could be used, a factor 2.5 smaller than the envisaged CMS and ATLAS High Luminosity upgrade and due to bump bonding size constraints probably not possible in HAPS technology. HV-CMOS (rf. Sect. 1.12.4) are probably the best candidates but they have to become faster and significantly more radiation hard. All in all, silicon sensor technology will be again the key to success, but still has to be developed; most probably with very good timing resolution.

Needless to say that challenges on other detectors and especially the accelerator are of equal or maybe even higher difficulty.

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[7] A factor we neglected in earlier chapters.

Final detector concepts will be defined by particle physics needs but it will be very challenging.

I like to cite a speaker from a recent (2017) conference talking about 500 million strips, ∼10 billion macro-pixel, ∼5.5 billion micro-pixels and the incredible high radiation levels:

Yes, we know this is crazy.

This will be fun!