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# Instrumentation at the LHC—The silicon tracking systems

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ABSTRACT

For the experiments at the Large Hadron Collider at CERN the detectors in the vertex region and the tracking systems are very critical components for the success of the projects. Due to the harsh environment at the high intensity hadron collider these detectors are also the most challenging to construct. The design of the experiments started about 25 years ago. At this time silicon detectors as particle detectors for high energy physics experiments were still in their infancy. But, because of the huge progress made in developing this technology all LHC experiments finally employed silicon detectors and some experiments even constructed very large silicon systems.

The LHC experiments went into operation in 2009, and after two years of operation the performance of the detectors can now be evaluated. This paper gives an overview of the different silicon detector systems at LHC and summarizes the installed silicon detector types and dimensions.

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## 1. Historical remarks

In the mid-1980s the project of a Large Hadron Collider at CERN utilizing the existing LEP tunnel with 27 km circumference was proposed. In the first presentations this project aimed for a centre of mass energy of 16 TeV and a luminosity of about $10^{33}\ cm^{-2}\ s^{-1}$. At the same time, the construction of the SSC in the USA had started an even larger project to build a proton–proton collider with a centre of mass energy of 40 TeV and a similar luminosity. The LHC project gained momentum and was soon seen as a competitor project to the SSC. A first optimistic time schedule of the LHC foresaw its completion well before the start-up of the SSC. It became however clear that—in order to beat the SSC for example on the search for the Higgs Boson—the lower collision energy of the LHC had to be compensated by a higher luminosity. This was the birth of the high luminosity LHC. A collider with a peak luminosity of $10^{34}\ cm^{-2}\ s^{-1}$ seemed feasible, but it was unclear how one could exploit such a high intensity machine with the detector technologies of those days.

The first experimental concepts focused on calorimetry and on the detection of muons. In these schemes the inner region of the experiments consisted of either absorbers (for a beam dump type experiment) or of transition radiation detectors and calorimeters. Outside of these inner detectors or absorbers, a muon spectrometer was envisaged to detect and measure muons. See Fig. 1 for an example of a detector concept discussed at that time.

It was a widespread belief by many physicists at these days that tracking or vertexing at such particle intensities would not be possible. Silicon detectors just started to be developed for high energy experiments. The first ever silicon microstrip strip detector, a surface barrier sensor, was tested at CERN a few years ago [2]. The first silicon detectors using the planar technology and implanted strips were installed in the NA11 experiment in 1983 [3]. Nevertheless, in the same conference (Como 1988) where beam dump experiments and calorimetry were discussed for the LHC, some foresighted colleagues proposed silicon tracking systems utilizing this new technology. In their paper [4] a multilayer silicon strip tracker was proposed with a projected silicon surface of 40 $m^2$—a design surprisingly close to some of the finally adopted detector layouts.

Between these early discussions on possible detector concepts and the start of the LHC experiments lie 30 years of remarkable progress in silicon detector technology, but also of substantial advances in the read-out and connectivity technology. Size and complexity of the detectors increased and silicon systems became indispensable components for high energy physics experiments. The employment of strip and pixel sensors in so-called vertex detectors opened up the window to heavy flavour physics. Meanwhile, no experiment in particle physics is designed without silicon sensors. Also more and more detector physicists in the field turned to silicon applications, thus making this detector community the fastest growing. Fig. 2 compares the number of institutes participating in the construction of silicon detectors during various time periods. The early microstrip detectors for fixed target experiments were built by only one institution (CERN; NA1 experiment, eight physicists) and by three institutions (CERN, MPI Munich, TU Munich; NA11 experiment). The experiment Mark II at SLAC and the LEP experiments (ALEPH, DELPHI, L3, and OPAL) at CERN used silicon vertex detectors for

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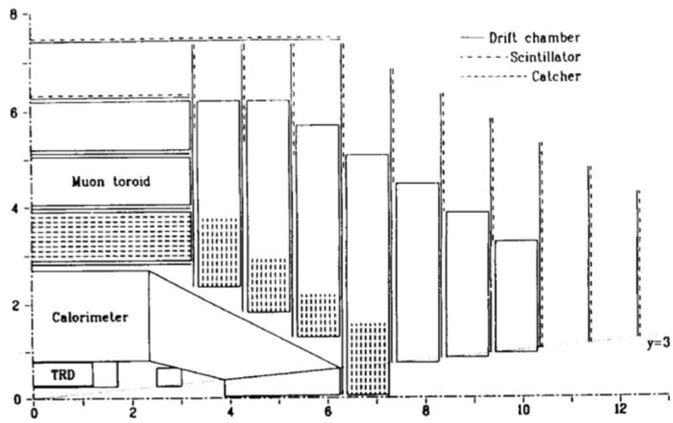


**Fig. 1.** Conceptual design for a non-magnetic detector at LHC or SSC [1].

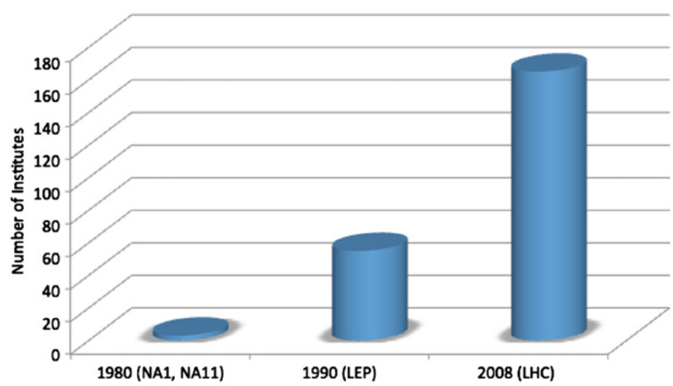


**Fig. 2.** Number of high energy physics institutes involved in the construction and operation of silicon detector systems: for the first detectors ever, for the LEP experiments, and for the LHC experiments.

the first time in a collider environment. The first vertex detectors, followed by several upgrades, were already designed and built by about 55 institutes. At present, for the LHC experiments about 165 institutes are developing, constructing and operating the various silicon detector systems.

At the time of the technical proposals for the LHC experiments, the acquired knowledge and the obvious advantages of high performance track reconstruction for the quality of the physics results led to the proposal of complex silicon tracking systems. The designs of the central trackers were optimized to reconstruct isolated high $p_t$ tracks and high $p_t$ tracks within jets with high efficiency over a large rapidity range. The momentum resolution for isolated charged leptons in the central rapidity region was aimed to be $\Delta p_t/p_t \approx 0.1 p_t$ ($p_t$ in TeV) in order to also allow the determination of the lepton charge up to about 2 TeV. For important discoveries the ability of b-tagging at highest luminosities was thought to be crucial. This requirement led to the proposal of layers of pixel detectors with a projected impact parameter resolution of the order of 20 μm for high $p_t$ tracks.

The LHC finally started regular operations in 2009. During the first years, the LHC produced proton–proton collisions with a centre of mass energy of 7 TeV at luminosities up to the design value of $10^{34}$ cm$^{-2}$ s$^{-1}$. Two running periods with colliding lead ions took place at the end of 2010 and 2011. In order to exploit the physics potential of this machine the four large experiments (ALICE, ATLAS, CMS and LHCb) and a few small experiments (TOTEM, LHCf) went into operation to record and analyse the collisions. The main silicon systems of these experiments will be explained in the following chapters.

## 2. ATLAS experiment

The ATLAS experiment (A Toroidal LHC ApparatuS) is a multi-purpose experiment placed inside a huge underground cavern [5]. The inner tracking system of ATLAS consists of a silicon hybrid-pixel detector in its centre, followed by the silicon strip detector, called SemiConductor Tracker (SCT), and the gas straw-tube Transition Radiation Tracker (TRT) surrounding the SCT.

The ATLAS pixel detector [5–18] consists of three barrel layers (1456 modules) and of three end cap discs (288 modules) on each side. The innermost pixel layer is placed at a radius of 50.5 mm from the beam axis. The pixel dimensions are $50 \times 400$ μm$^2$. The total number of read-out channels of this device is 80 million—this makes the ATLAS pixel detector the largest pixel detector installed at the LHC.

Surrounding the pixel detector is the ATLAS SCT [7] consisting of four barrel layers (2112 modules) and nine end cap discs on both sides (1976 modules). The SCT has a radial coverage of 30 cm $< r <$ 52 cm, and extends up to $|\eta| = 2.5$ in pseudorapidity. The silicon area of the SCT is 61 m$^2$ with a total of 6.3 million read-out channels.

A charged track originating from the vertex region traverses first three layers of the pixel detector, then eight silicon strip layers before it enters the transition radiation tracker, where it generates hits in 36 straw tubes. The performance of these detector systems was excellent during the first years of operation with results close to the design values. For details about the performance of the ATLAS pixel detector and of the SCT see for example Refs. [8,9].

## 3. ALICE experiment

The ALICE Experiment (A Large Ion Collider Experiment) [10] is dedicated to the exploitation of the heavy ion mode of operation of the LHC. Compared to proton–proton collisions a much lower luminosity of about $10^{27}$ cm$^{-2}$ s$^{-1}$ is anticipated during heavy ion collisions. However, due to the nature of these collisions much larger charged multiplicities are produced per event. The ALICE experiment was designed to cope with a maximum charged particle multiplicity of up to 8000 per unit of rapidity. Obviously, these different experimental conditions led to a different detector layout compared to the other LHC experiments. The main tracking detector of ALICE is a huge time projection chamber—the biggest ever built. The TPC has a length of 5 m, an inner radius of 0.85 m, and an outer radius of 2.5 m resulting in a gas volume of 88 m$^3$. Positioned at radii below 0.5 m, there are three silicon sub-detectors.

The innermost detector is a two-layer Silicon hybrid Pixel Detector (SPD) with pixel dimensions of $50 \times 425$ μm$^2$, and 9.8 million pixels [11].

Surrounding the pixel detector are two layers of Silicon Drift Detectors (SDD) [12]. The ALICE SDD is the only silicon drift detector used in the LHC experiments. It covers a surface of 1.31 m$^2$ with (only) 133,000 read-out channels. It is a detector offering a compromise between precisely measured two-dimensional points and a reduced number of read-out channels. To reach the required precision an elaborate alignment and correction procedure is however required. As an example, the effect of the correction for the non-uniformity of the drift velocity on the alignment of the ALICE SDD is shown in Fig. 3.

The third and outermost silicon detector consists of two layers of Silicon Strip Detectors (SSD). The SSD is built out of double-sided strip detectors, covering a surface of 5 m$^2$, and consists of 2.6 million read-out channels.

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