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Silicon tracking detectors—historical overview

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Abstract

Semiconductor detectors have been known for more than 50 years, however their tracking capabilities, exhibiting spatial resolution in the 5–10 μm range, began to be explored only in the beginning of the 1980s, when experimental physics began to search for detectors to measure short-living particles. The introduction of planar technology provided a boost to the industrial production and use of silicon strip detectors. The next essential step came with the development of a dedicated VLSI readout, which allowed for integration of detectors and electronics. Efforts towards obtaining two-dimensional detectors were initiated right from the beginning, with CCD devices being the subject of early investigation. A second line of development involved pixel devices with thick sensitive layers—they began to be successfully implemented in experiments towards the end of the 1990s. Radiation effects in detectors and electronics were recognized early, however it took many years to understand the physics of radiation damage—currently, we possess detectors and electronics capable of surviving doses of 10 Mrad and fluxes of 10^{14} neutrons/cm^2, or higher. Nowadays, all particle physics spectrometers have inbuilt vertex detectors, which deliver excellent results. The application of silicon tracking detectors has expanded to nuclear physics, solid-state physics, astrophysics, biology and medicine.

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Keywords: Silicon strip detectors; Charge coupled devices; Silicon pixel detectors; Particle physics experiments; Vertex detectors

1. Introduction

Silicon detectors have been known for more than 50 years [1–3]. In the beginning, they were widely used in nuclear physics; however, their application in particle physics was limited. Some examples are presented below:

- in recoil telescopes supporting experiments at LBL Berkeley [4], JINR Dubna and IHEP Serpukhov [5],
- to measure muon fluxes in the CERN SPS accelerator [6],
- as active targets in experiments at CERN [7].

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The discovery of particles such as heavy quarks, which travel several millimetres before decaying, has focused the interest of the high-energy physics community on silicon detectors and their tracking capabilities [8].

2. Silicon tracking in HEP experiments—the beginnings

2.1. First silicon strip detectors

Towards the end of the 1970s, several groups involved in charm quark production studies at CERNs SPS accelerator [9,10] were searching for new devices which could identify and measure particles with lifetimes in the order of 10^{-13} s. The Pisa group investigated the use of silicon detectors as elements of an active target, in which one could identify the appearance of a secondary vertex by observing a step in the amplitudes of signals from thin detectors. To improve the signal-to-noise ratio, the authors subdivided the metal electrodes into strips, each with a capacity significantly lower than the whole detector, to be read out separately. Such devices, called "multielectrode silicon detectors" (MESD) or "miniaturized multiwire proportional chambers" were built on silicon disks with a diameter of 23 and thickness of 1 mm, with a pitch of 300 μm—see Fig. 1; for minimum ionizing particles, full efficiency was achieved at biasing voltages above 150 V and the signal-to-noise ratio was about 10 [11].

At approximately the same time, the CERN group constructed strip detectors for high-precision tracking using silicon wafers of $24 \times 30\,\mathrm{mm}^2$ and 400 μm thickness, and with a strip pitch of 100 and 200 μm—Fig. 2. The detector was equipped with an analogue readout (hybrid preamplifiers and standard ADCs) and was tested in the NA11 setup at CERN, exhibiting efficiency in excess of 99%, good spatial resolution (most of the hits were on a single strip) as well as good stability. The usefulness of this detector for precise vertex reconstruction was also demonstrated [12].

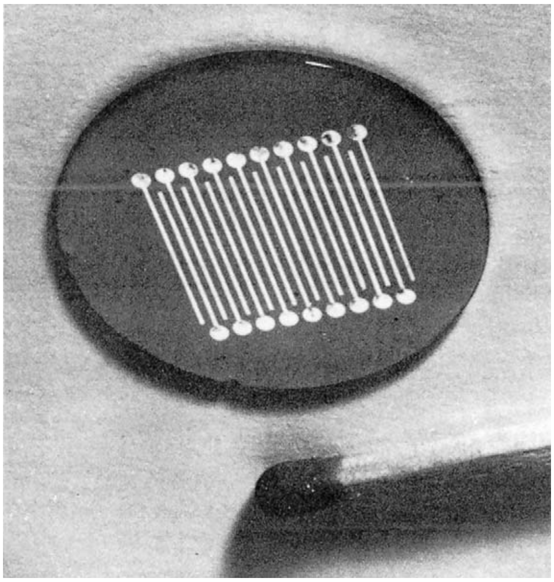

Fig. 1. Silicon strip detector built by the Pisa group [11].

Both of the above prototypes were constructed as surface barrier silicon diodes on high resistivity n-type silicon, which allowed to deplete the whole thickness of the detector at about 120–160 V bias voltages (depending on the thickness) and to collect all deposited charges. However, the technology of manufacturing these detectors was rather tricky, thus limiting their availability. In 1980, a paper on production of silicon detectors using the standard planar process was published [13], in which it was demonstrated that the high-temperature oxidation process does not damage high-resistivity silicon, required to produce good detectors with small leakage currents and good charge collection. It was an essential step towards the industrialization of these devices.

2.2. First use of silicon strip detectors for tracking

The NA11/NA32 experiments were the first to use a set of silicon strip detectors for tracking and vertex measurements [14–16]. The 1981 installation included six planes of silicon strip detectors with dimensions of $24 \times 36\,\mathrm{mm}^2$, produced on 2 in. n-type silicon wafers, with a resistivity of 2–3 kΩ cm and a thickness of 280 μm, using the planar process. The pitch of these detectors was 20 μm, however capacitive charge-division was

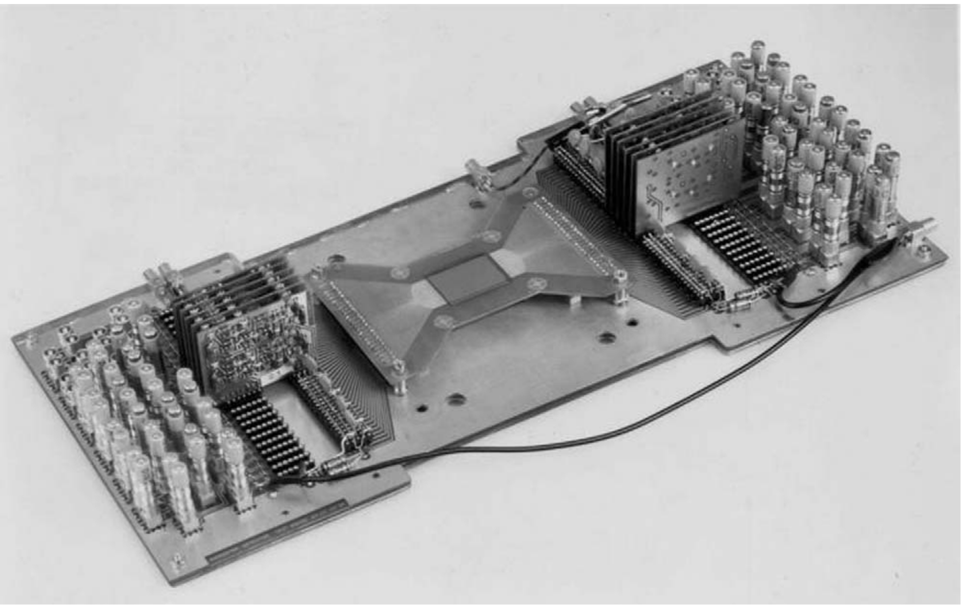

Fig. 2. Silicon strip detector built by the CERN group [12].

used and only every 3rd (or every 6th) strip was actually read out. Fanning out was done by bonding detector Al strips to PCB Cu-lines—Fig. 3 shows a photograph of a mounted counter. The signal-to-noise ratio was about 30 for minimum ionizing particles and the spatial resolution was 4.5 μm for 60 μm and 7 μm for 120 μm readouts.

In a second setup, eight detectors were grouped into four pairs (one in front of the target, three behind) having strips at ±14° stereo angles. The performance of the telescope was excellent: the vertex position along the beam was reconstructed with a precision of 130 μm and the impact parameter was equal to about 24 μm. Fig. 4 shows the event display of the production and decay of a D^- into $K^+\pi^-\pi^-$ [15].

The progress on silicon strip detectors attracted experimental physicists at CERN, Fermilab and JINR Dubna and several interesting developments were reported at the 3rd European Symposium on Semiconductor Detectors in Munich, November 1983 and at the 1984 IEEE Nuclear Science Symposium [17–19].

2.3. Towards two-dimensional detectors

Silicon strip detectors carry the disadvantage of projective geometry, which creates problems with signal assignment at high multiplicities, particularly pronounced in jet-type events. Therefore, a search for detectors with two-dimensional readouts was pursued. In 1982, the Rutherford Laboratory group published results, showing that standard Charged Coupled Devices (CCD) could be used for recording of minimum ionizing particles [20]. The signal obtained from a very shallow depletion region of CCD (about 16 μm) was small (about 1300 e–h pairs); however, the dark current noise was substantially suppressed by cooling the detector to liquid nitrogen temperatures—the efficiency of the detector was about 98% and the spatial resolution σ_x and σ_y was in the range of 4.3–6.1 μm.

Such detectors were first used in the vertex telescope of the NA32 experiment at CERN [21], a descendant of the NA11 experiment—see Fig. 5a, giving excellent results—see Fig. 5b. The history of

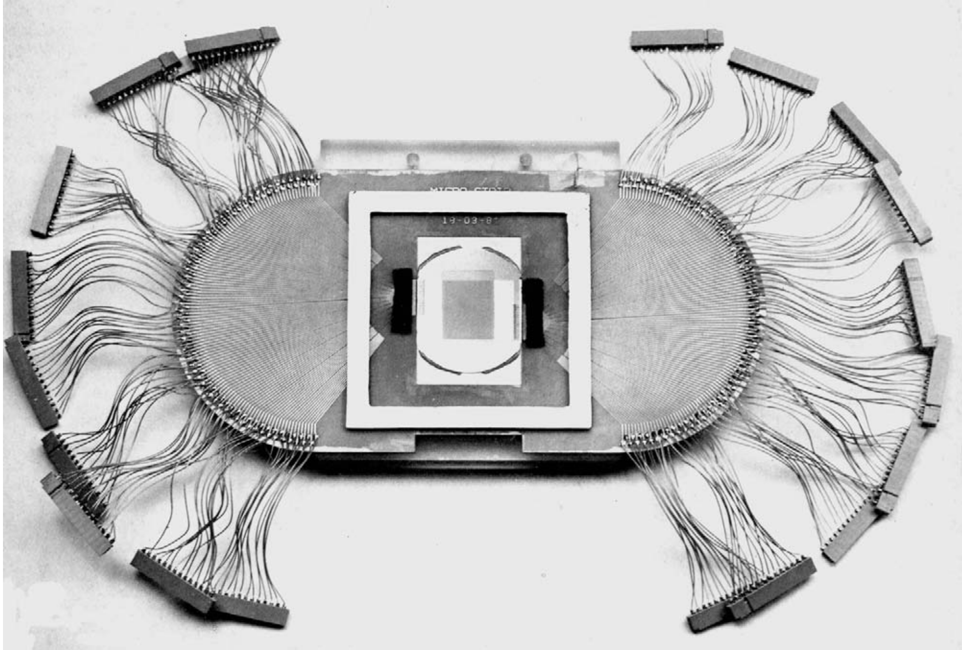

Fig. 3. Silicon strip detector assembly used in NA11 experiment at CERN [14–16].

these detectors and their use is presented in a dedicated talk at this conference [22].

A novel type of tracking detector, the “semiconductor drift chamber”, was proposed in 1984 [23]—detectors of this kind are covered in a separate talk at this conference [24]. The two coordinates are given by the anode number and the drift time of deposited charges. To avoid overlapping of signals from consecutive events, these detectors are used in experiments at rather low rates (the time interval between events should be larger than the drift time).

3. Progress on readout electronics

As can be seen in Fig. 3, the detector assembly of NA11/NA32 was rather bulky, which was acceptable for fixed-target experiments, however, it could not be used in collider experiments. Therefore, it became imperative to look for other solutions and in 1984 some new ideas on VLSI electronics were presented [25,26]. Soon after that Microplex and Camex chips were produced [27,28]—it was a very essential step in further development of silicon tracking detectors.

Successful tests of silicon strip detectors with VLSI readouts were carried out in 1985 [29,30] paving the way towards collider vertex detectors. Fig. 6 shows the n-MOS readout chip, Microplex, attached to a strip detector via ultrasonic bonding.

Soon after these first demonstrations, the next generation of VLSI CMOS chips, SVX [31] and MX [32], with more sophisticated logic, was developed. These chips were designed for vertex detectors at LEP and Tevatron.

One of the best front-end designs, with noise figures $\mathrm{ENC} = 160\mathrm{e}^- + 12\mathrm{e}^-/\mathrm{pF}$ for the integration time of a microsecond, was the “Viking” (VA) chip [33], different versions of which have been used in various applications and particle physics experiments.

Plans for high-energy hadron colliders, SSC in the USA and LHC in Europe, brought up new design requirements, namely high-speed and radiation hardness, which in conjunction with other

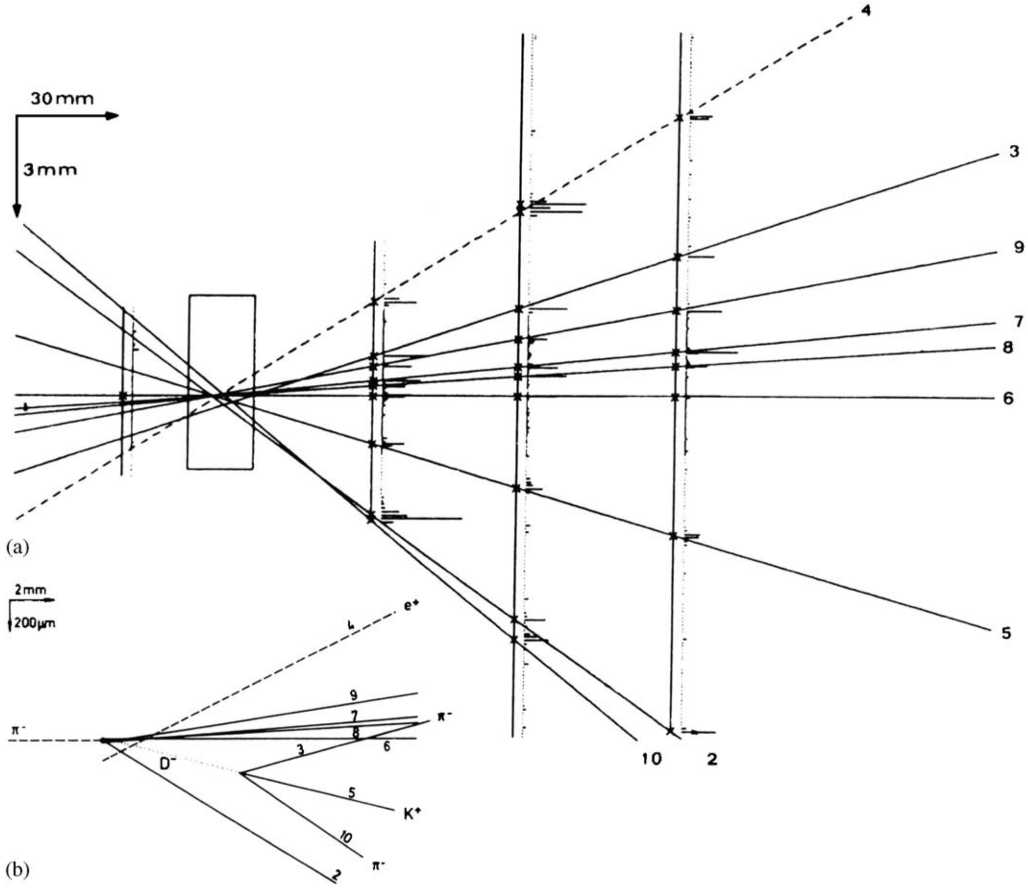

Fig. 4. Event display of an interaction in Be target of NA11 experiment at CERN, showing tracking and vertexing capabilities (2 planes of detectors in front and 6 beyond the target are marked; horizontal lines attached to these planes represent amplitudes of recorded signals) [15,16].

conditions, such as a long pipeline, low noise and low-power consumption, made the task close to impossible. First prototype designs relied on bipolar analogue front-ends and digital CMOS elements, produced as separate radiation-hard chips and wire-bonded together [34]. Other designs looked towards new chip architectures, which could be implemented in radiation-hardened CMOS technologies [35,36]—the prototypes exhibited good electrical performance, however radiation hardness varied from run to run. The radiation-hard DMILL technology, which combined bipolar and CMOS processes on one chip [37], and which became available for external users [38] brought hope. A number of successful designs were completed, among them the ABCD readout chip for the ATLAS SCT tracker [39], which satisfies tough LHC requirements.

Towards the end of the 1990s, it was found that at sub-micron feature sizes, the electronics become radiation-tolerant, even when using the standard industrial process, because of the tunneling of charges from very thin gate oxide layers [40]; such designs, however, required special libraries with “edgeless” transistors. The sub-micron technology, a standard in the modern electronics industry, opened up new possibilities for low-cost radiation-hardened readout electronics for HEP detectors

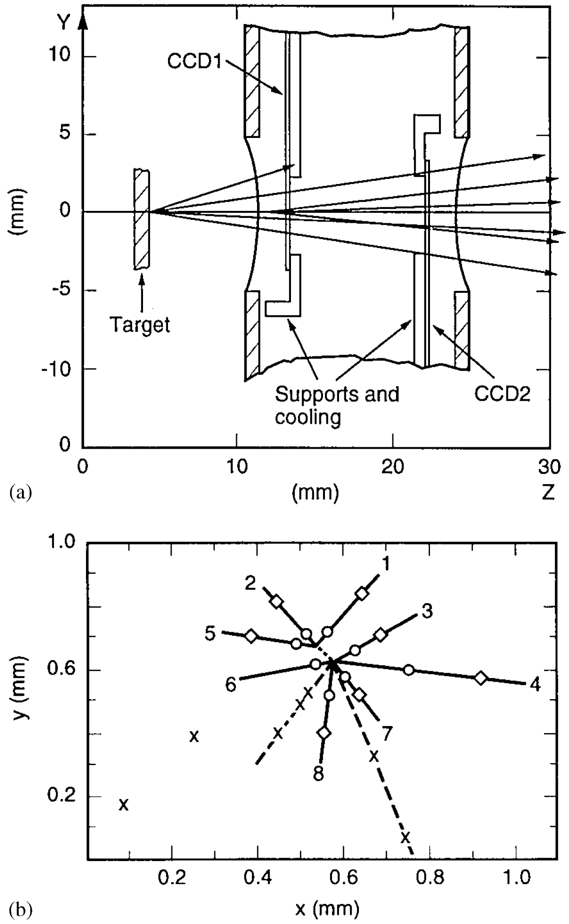

Fig. 5. Installation of two CCDs in the NA32 experiment at CERN (a) and an event display with two vertices (b); detector frame is $1 \times 1\,\mathrm{mm}^2$; hits in the first plane are marked with circles, and in the second plane—with diamonds.

and many successful designs are already available [41,42].

4. Silicon vertex detectors for e^+e^- experiments

The potential of high-precision silicon tracking was recognized by several experiments right from the beginning; however, it took some time to convince others. The first collider-type silicon vertex detector was installed in Mark II at SLC [43]—it had the size of a coca-cola can (see Fig. 7)—yet it helped essentially in precise vertex measurements.

The device consisted of 36 detector modules, with 72, 82 and 90 mm silicon detectors, each with 512 strips and the pitch of 25, 29 and 33 μm, respectively, being read out by four Microplex chips. The closest layer was placed at a distance of 29 mm from the beam line, and the asymptotic impact parameter resolution was better than 10 μm.

At LEP, the first silicon vertex detectors were installed in DELPHI [44] and ALEPH [45] experiments, with OPAL joining soon [46], and finally also in L3 [47]. The first DELPHI vertex detector, consisting of two layers of single-sided strip detectors (192 detectors with 55,296 readout channels altogether) was constructed in 1989; it went through several upgrades and finally, in 1996, a $1.7\,\mathrm{m}^2$ detector was built out of 888 detectors, with 1,399,808 readout channels (736 strip detectors with 174,080 readout channels, and 1,225,728 pixels)—see Fig. 8 [48].

The performance of the vertex detectors at LEP2 is summarized in Ref. [49]. They were great detectors, providing a lot of good physics.

The best "ever" vertex detector at the collider, VXD3, was constructed for the SLD experiment at SLC in 1996 [50]. It was a result of long-lasting efforts of the Rutherford group, which in an ingenious way, combined the potentials of CCDs with the low interaction rate and very small beam spot of the SLC collider. The history and performance of this detector and its predecessor are discussed at this conference [22]; here only the final results—the impact parameter resolutions—are presented (Fig. 9).

In the recent years, silicon vertex detectors for CLEO [51], Belle [52] and BaBar [53] experiments were constructed and successfully used.

5. Silicon detectors at the Tevatron and HERA

The CDF experiment was amongst the first which used silicon vertex detectors—their initial application dates back to the end of the 1980s [54]. In the recent years, the hardware was upgraded and the present detector for run II has reached a

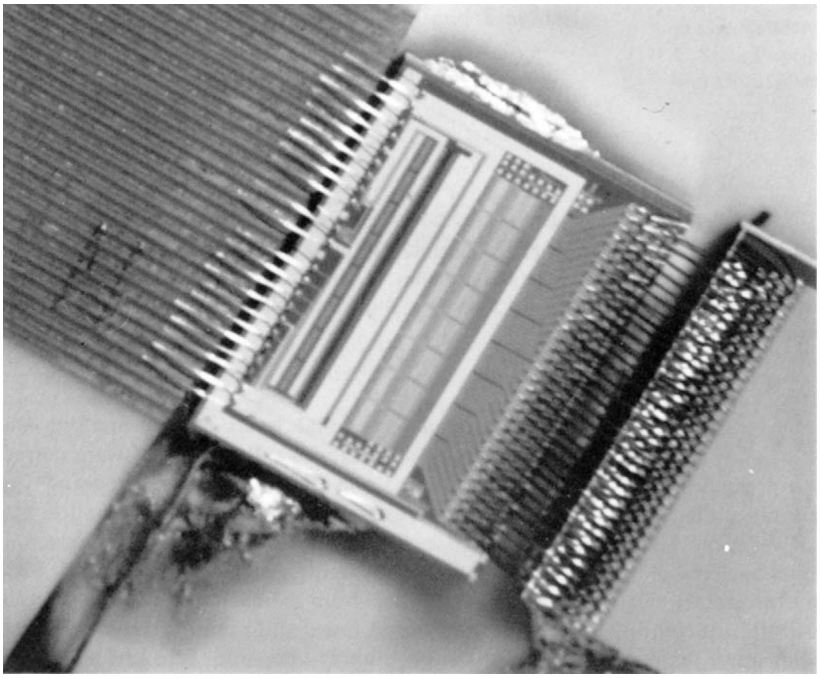

Fig. 6. Microplex readout chip bonded to a silicon strip detector [29].

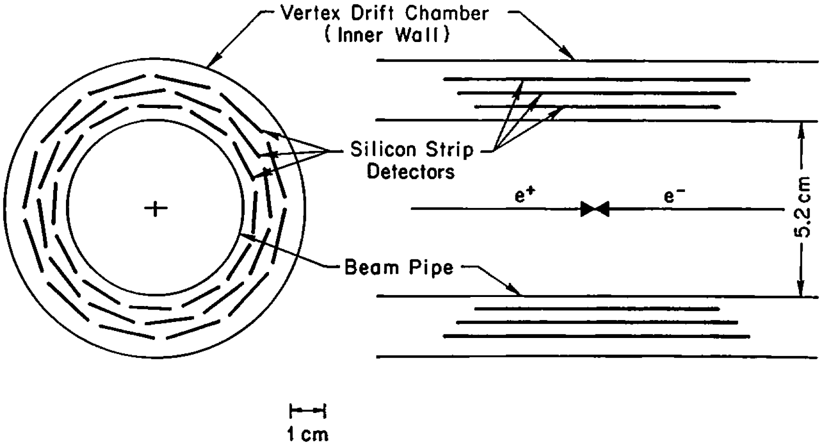

Fig. 7. The layout of the Mark II Silicon Strip Vertex Detector [33].

diameter of 64 cm and the total length of 190 cm [55]. It comprises three sub-detectors: a vertexing layer 00 at the 1.5 cm radius, five layers of SVX II between the 2.5 and 10.6 cm radii, with a length of 90 cm, and two ICL cylinders at the 20 and 28 cm radii, with a length of 190 cm—altogether 704 ladders with 722,432 readout channels. The readout chip SVX3D follows from the SVX line [31], with substantial upgrades to its functionality as well as radiation resistance.

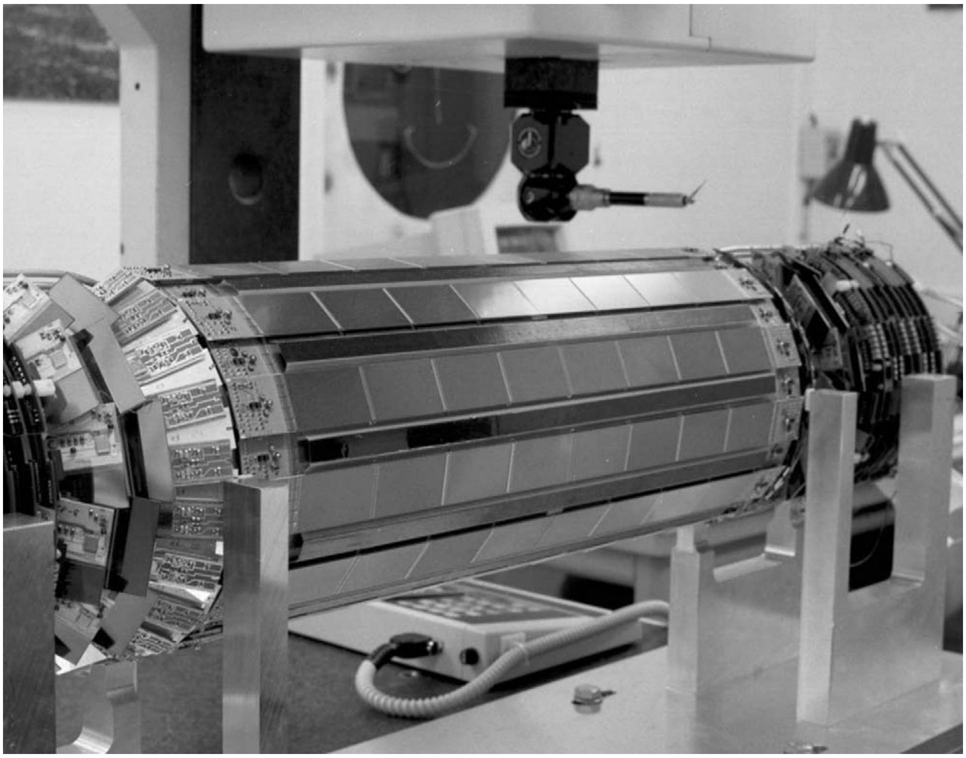

Fig. 8. The latest version of the DELPHI silicon vertex detector at the metrology stand.

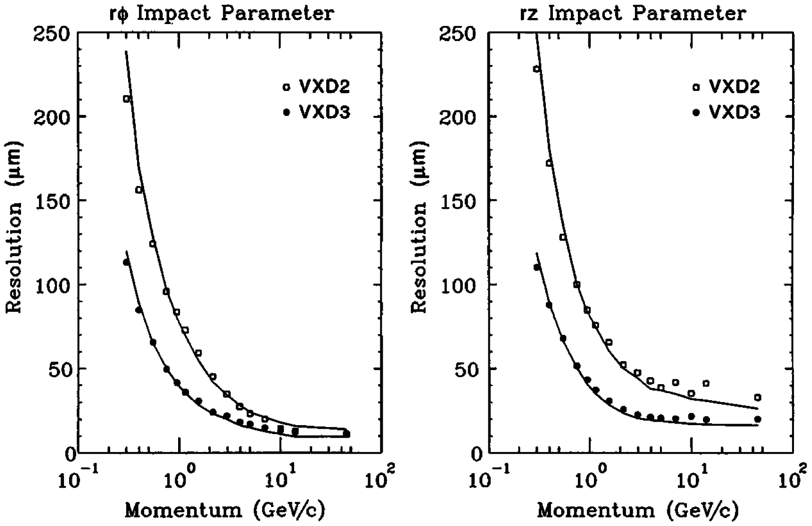

Fig. 9. Measured impact parameter resolution of VXD2 and VXD3 compared with Monte Carlo simulations [50].

The D0 Microstrip Silicon Tracker (MST) has been commissioned in 2001; it consists of six 12 cm long barrels, each with four detector layers, interspaced with detector disks, and two stacks of forward disks covering the forward region down to a pseudo-rapidity of 3 [56]. Single- and double-sided detectors are used; altogether there are 792,576 channels, read out by SVXIIe chips.

The CDF and D0 trackers were successfully commissioned and operate well, providing prompt data of selected B or D meson channels for calibration, which were very difficult to measure in the past. The commissioning experience provides valuable lessons for future large silicon trackers, concerning large system aspects (such as powering and cooling) as well as testing (grounding, shielding).

CDF and D0 silicon trackers are also used in the second-level trigger, which provides impact parameters for online preselection [57,58]. The effective impact parameter resolution for both detectors is about 35 μm, which reflects very good mechanical alignment.

Both H1 and ZEUS spectrometers are equipped with silicon vertex detectors which significantly enhance their physics potential [59,60].

6. Development and use of pixel detectors

As the CCD had several limitations to their use in particle physics for charged particle detection, it was natural to look for detectors which would provide more flexibility. Two lines of development were pursued: hybridization of detectors and readout electronics, which allowed for optimization of each of them prior to assembly, and monolithic designs, which required that new ideas and technologies be explored.

In 1984, it was shown that a Ge PIN diode array could be connected to a readout chip by bump bonding [61]. Work in this direction was carried out in Europe and United States, and first results from hybrid pixel detectors for particle physics were presented in the early 1990s [62,63]. More or less at the same time, initial results of monolithic prototype research were shown [64,65].

In parallel, with the development of new technologies, pixel detectors gradually entered usage in experiments at CERN: WA97 [66], DELPHI [48] and NA60 [67].

Today, several new technologies are emerging, in particular Monolithic Active Pixel Sensors a nd three-dimensional pixel devices—both being extensively covered at this conference [68,69].

7. Silicon detectors for high luminosity machines

The potential of silicon detectors, in particular their high granularity and precision, as well as radiation hardness, was recognized when the preparations of experimental programs for SSC and LHC supercolliders started [70,71]. Several dedicated workshops took place and vigorous R&D activities were launched in the US and in Europe; they were oriented at radiation effects on silicon detectors at high neutron and ionization radiation doses, optimization of strip and pixel designs, development of fast readout electronics and its implementation in radiation hard versions.

Radiation effects in silicon strip detectors, namely the increase of leakage currents and changes in effective doping concentrations, were already noticed in NA11/NA32 experiments—they coincided with the beam profile [72]. Systematic studies were carried on in the US [73–75], Japan [76–78] and Europe [79–81], with detectors on various materials, exposed to various types of radiation. The most complete summary of all data was given by the ROSE collaboration at the previous Hiroshima symposium [82]. The important facts are:

- the leakage current increases with radiation proportionally to the fluence (see Fig. 10):

  $$I = \alpha \Phi_{\mathrm{eq}} V;$$

  $$\alpha_{80,60} = (3.99 \pm 0.03) \times 10^{-17}\ \mathrm{A\ cm},$$

  where α is a constant, Φ_{eq} is the equivalent fluence, and V is the volume;
- the effective doping concentration, which leads to type “inversion”, changes according to the

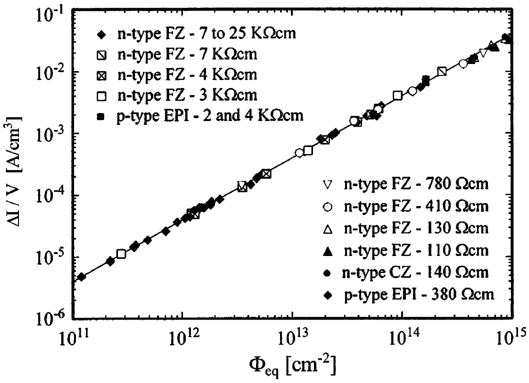

Fig. 10. Fluence dependence of leakage current for detectors from various suppliers produced on various materials [82].

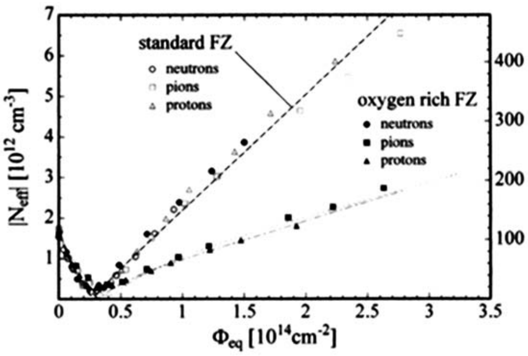

Fig. 11. Dependence of N_{eff} on the equivalent 1 MeV neutron accumulated fluence, for standard and oxygen-enriched FZ silicon, irradiated with neutrons, protons and pions [82].

formula (see Fig. 11)

$$\Delta N_{\mathrm{eff}}(\Phi_{\mathrm{eq}}, t(T_{\mathrm{a}})) = N_{\mathrm{A}}(\Phi_{\mathrm{eq}}, t(T_{\mathrm{a}})) + N_{\mathrm{C}}(\Phi_{\mathrm{eq}}) + N_{\mathrm{Y}}(\Phi_{\mathrm{eq}}, t(T_{\mathrm{a}})),$$

where N_{A} is the short-term beneficial annealing, N_{C} is the stable damage part, N_{Y} is the reverse annealing component, and T_{a} is the annealing temperature.

The summary of these studies is that silicon detectors at larger radii will operate at LHC for more than 10 years, however they must be prepared to run at much higher voltages than initially, and that leakage currents as well as dissipated power, could be substantial.

There are also several new ideas for pixel and/or strip detectors, using diamond as the base material [83] or using silicon in cryogenic temperatures [84]—both appear interesting for future experiments at very high luminosities.

8. Large silicon trackers for LHC experiments

All four LHC experiments use silicon detectors in their central vertexing/tracking systems; these detectors have been described in many reports and publications, including contributions to this symposium [85–88]. They use all kinds of technologies—pixels, strip and drift detectors, and they are read out by radiation hard electronics, fabricated mainly in submicron commercial processes. As mentioned before, these detectors have to withstand very high collision rates, and have to survive large fluences of neutrons and ionizing radiation. In addition, one has to grant provisions for an exchange of vertex layers during the lifetime of the experiment.

The scale of these detectors, which in the case of ATLAS reaches about 70 m^2 and for CMS, about 210 m^2 of active silicon, subdivided into many thousands of detector modules is new. The assembly, testing, calibration and mounting of such large numbers of components require adequate, highly automated approaches, with computerized operations and data recording. To obtain high-quality detector modules, produced at various assembly sites, CMS has standardized their automatic assembly equipment—see Fig. 12 [86]. ATLAS qualifies every assembly site prior to mass production and it plans to use “robots” for placing detector modules on support structures—see Fig. 13 [85].

9. Silicon tracking detectors in space projects

Silicon trackers for ALPHA Magnetic Spectrometer (AMS) and Gamma-ray Large Area Space Telescope (GLAST) will be mentioned here for completeness; details of their parameters, con-

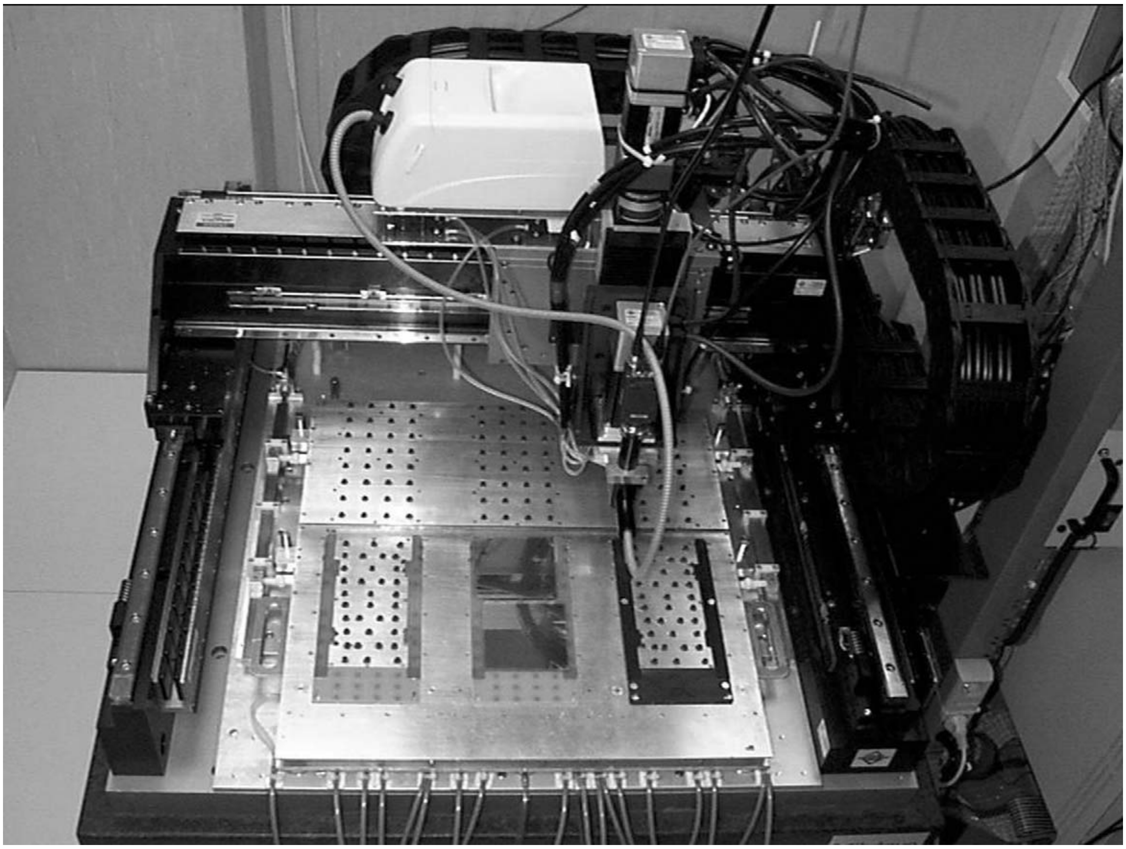

Fig. 12. CMS silicon detector module assembly equipment [86].

struction and performance can be found in several presentations at this symposium [89–92]. Both of these instruments use large area of silicon for tracking, with the lightness, low-power consumption, robustness and reliability being of prime importance.

The AMS project has commenced at the beginning of the nineties. The apparatus contains a magnetic spectrometer, consisting of a superconducting magnet of 0.8 T field, equipped with eight planes of double-sided silicon strip detectors (strip pitch 27.5 μm on p-side and 52/104 μm on n-side) arranged in long ladders (in total ~2500 sensors covering $\sim 6\,\mathrm{m}^2$), to measure momenta, charges and mass of the particles. The prototype device AMS-01 has flown on the Space Discovery shuttle in 1998, demonstrating good performances (space resolution $\sigma_\mathrm{p} = 8.5\,\mu\mathrm{m}$, $\sigma_\mathrm{n} = 30\,\mu\mathrm{m}$) and providing valuable physics results. The next mission with a new AMS-02 detector is scheduled for 2007.

GLAST started in 1997, with a goal to put the telescope on the orbit for a 5-year mission in 2007. The device is built of 16 towers, each consisting of a silicon tracker equipped with conversion foils—to observe gamma conversion, and an electromagnetic calorimeter—to measure the energy of electron pairs; all shielded by scintillation anticoincidence counters. The silicon tracker consists of 36 layers of silicon strip detectors (AC-coupled, single-sided, 228 μm pitch, manufactured on 6 in. wafers)—in total (including 2 calibration modules) 10,368 detectors covering surface of about $80\,\mathrm{m}^2$ (!), and 880,000 strips equipped with low-power

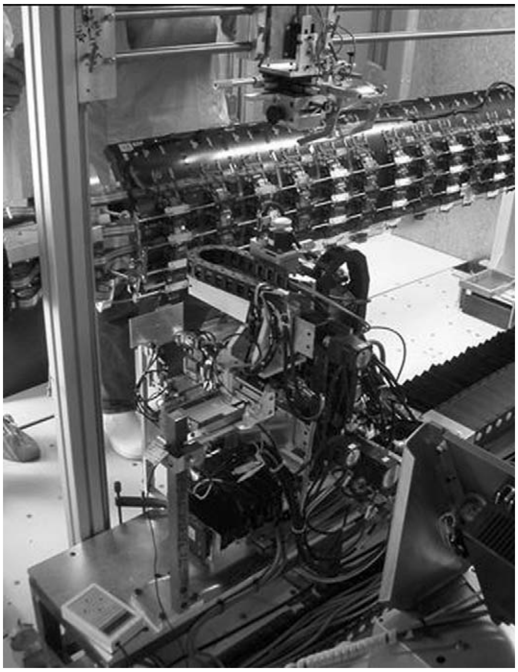

Fig. 13. ATLAS SCT robot for placing silicon detector modules at the barrel support structures [85].

electronics (125 mW/layer). A prototype tower has been assembled and tested, confirming the design parameters.

10. Summary

In 2004, we "celebrate" the 25th anniversary of the use of silicon tracking detectors in particle physics. This period has witnessed fantastic technological developments based on the imagination of inventors and the use of commercial silicon technology. Today all spectrometers are built with silicon vertex detectors and these detectors deliver very essential physics results for particles with heavy quarks, their production mechanisms, lifetimes, mixing, etc. Silicon trackers are fundamental components of future experiments in large laboratories and in space, while silicon position detectors are finding their way into many applications beyond particle physics. The progress achieved thus far is very vividly demonstrated by this symposium and many other workshops and conferences [93–102].

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