7.7 The LEP Silicon Vertex Detectors: Right on Target

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After their successful use in fixed target experiments for charmed physics starting in the early 1980s [Highlight 5.9], innovative silicon strip detectors were developed and successfully operated in experiments at colliders like LEP. One major motivation was the study of particles containing heavy flavour quarks, charm or beauty. These particles are short-lived with lifetime τ of the order of 10^{-12} s (1 ps). To tag such particles the transverse accuracy of extrapolation of the tracks of the particle decay to the interaction point (IP) must be better than their characteristic offset $c\tau = 300$ μm. This requires excellent spatial resolution of the detectors, a minimal distance to the IP and minimal thickness of material traversed by the particles. Material affects the direction of the particles, whence deteriorating the extrapolation accuracy. A collider imposes further constraints. The innermost radial position of the detectors is fixed by the radius of the beam pipe, the outermost one by the size of the first tracking chamber. Installation and removal of the complete Si detector system must be possible independent of the other detectors. Layers of silicon strip detectors were arranged in concentric cylinders around the beam pipe. The radius r of the detector wafer, given by the holding frame, provided the r coordinate. The detectors had readout (RO) strips on both sides, parallel (for Φ coordinate) and perpendicular (for z coordinate) to the beam, respectively, allowing space measurements. The RO electronics was normally mounted along two edges of the detector wafer, adding extra material and distributing the heat load throughout the volume of the detector. Solving these problems was a major challenge at LEP, as described here.

A major direction of research addressed the two-sided RO of the Si-detectors. This is made difficult by an e^- accumulation layer at the Si-SiO_2 interface on the ohmic or n-side of the detector, which lowers the inter-strip resistance, hence sharing the charge over many RO strips. The strips must thus be insulated from one another. To disrupt the e^- layer, ALEPH and DELPHI used blocking p+ electrodes between the n strips. DELPHI used AC-coupled readout strips with a width larger than the n-strip implants, and at a negative potential compared to these implants for insulation.

The ALEPH Silicon Vertex Detector [44] was the first detector operating in a collider to use the two-sided RO. The achieved spatial resolution of the complete device (intrinsic plus alignment) was 12 μm in the r–Φ view and 12 μm in the longitudinal z view. Two detectors each were mounted onto one electrical building block, the “module”, and two modules were mounted together lengthwise to form the basic mechanical building block of the system, the “face”. The inner layer consisted of 9 mechanically independent faces, the outer layer of 15 faces, making a total of 2 × 24 electrically and mechanically identical and independent modules. Each module contained two identical Si wafers, the hybrids with RO electronics and connections. Most components were custom-made.

The design of the detectors was the result of an intense R&D program carried out over several years. It introduced a novel biasing scheme which made it possible to deplete the entire detector volume using only two contacts, one for the p+ side and one for the n+ side. Due to the capacitive charge sharing between RO strips, only every fourth p+ strip on the junction side and every second n+ strip on the ohmic side were connected to the readout electronics.

With only a modest degradation in terms of material and an acceptable ambiguity level, the RO traces were routed on separate thin substrates. The Z-strips were wire bonded to diagonal RO strips at the edge of the detector, the signals being carried to the electronics in a zig-zag geometry, using additional Z-strips to link the diagonal ones (Fig. 7.16).

The RO chip was a custom-designed with 64 parallel channels arranged in a RO pitch of 100 μm (CAMEX64, CMOS Amplifier with MultiplEXing 64 channels). It was developed in CMOS technology in collaboration between the Max Planck Institut für Physik, Munich and the Fraunhofer Institut, Duisburg. The readout electronics for the Φ and Z-strips of each module consisted of two different ceramic printed circuits equipped with their readout chips and surface-mount components.

DELPHI [45] operated with a silicon strip microvertex detector from the start of LEP in 1989, initially consisting of two concentric layers of single-sided (SS) detectors providing high precision Φ measurements. In 1991 a third layer was added after the installation of a smaller diameter beam pipe. The detector achieved an averaged single hit precision of about 8 μm and a detection efficiency of 98%.

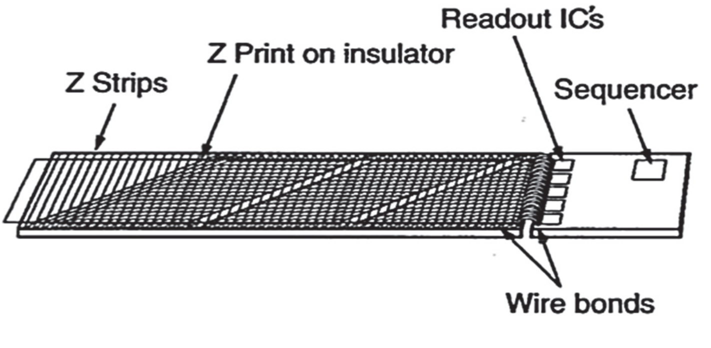

Fig. 7.16. The Z-strips are wire bonded to diagonal RO strips at the edge of the detector. (Courtesy C. Damerell)

The 1994 upgrade of the detector provided 3-coordinate measurements without degrading performance. It used double-sided (DS) detectors with orthogonally oriented RO strips on opposite faces of the detector wafer. In order to maintain the same material thickness, DELPHI developed DS detectors with a second metal layer on the ohmic surface making it possible to read-out the signal from both sides at the same end of the detector. In 1996 a further upgrade increased the solid angle coverage to improve the LEP2 BEH boson searches.

A process was developed using two metal layers, about 1 μm thick, separated by an insulating layer. The first layer coupled capacitively to the n+ side. Two different approaches to insulate the second metal layer were used in the industrial production: a low temperature deposition of oxide over the whole surface including the metal and an application of a film of Polyimide with an electric permittivity of 0.3 pF/cm. In both approaches tiny holes were opened in the insulating layer, such that the second metal layer, deposited on top could make the desired connections to the first metal layer and the orthogonal readout lines. The top lines ran parallel to the p+ diodes on the other side of the silicon. In this way all the signals could be read out at a common edge of the detector.

Constructing DS double metal layer detectors with integrated coupling capacitors and polysilicon resistors required 12 to 15 different masks compared with the 5 masks needed for a SS detector. Figure 7.17 shows a perspective view of the structure. Details are discussed in [45].

One more trick was used by DELPHI. Traditionally, the corresponding RO lines of the two detectors forming a half-module were "daisy-chained" together. However, since the RO lines of both sides are at the same potential one can join the n-side of one to the p-side of the other. This so-called flipped module design equalized the noise on the two sides and resolved ambiguities measuring the polarity of the deposited charge.

DELPHI also introduced the first forward pixel detectors at an e^+e^- collider [46].

These few technical details give a taste of the many challenges that were faced in order to optimize the use of this type of detector. Other aspects included cooling, radiation hardness, monitoring of radiation dose, shielding against electrical noise, data acquisition, offline reconstruction and alignment.

The other two LEP experiments, L3 and OPAL, also had excellent micro-vertex detectors [47, 48], while the rival SLD experiment, at the Stanford Linear Collider, used a novel CCD detector concept [49], benefiting from a smaller beam pipe radius. These vertex detectors were essential for all LEP heavy flavour physics.