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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Experience with the construction, operation and maintenance of vertex detectors at LEP

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Abstract

All major LEP experiments are equipped with silicon strip vertex detectors. Most of them have been upgraded several times to improve their performance and to match LEP2 requirements. The article reviews and compares the concepts of the vertex detectors at LEP and focusses on the experience gained by the detector groups. Solutions to problems encountered during construction and operation are discussed and aspects concerning maintenance presented. © 1998 Elsevier Science B.V. All rights reserved.

1. Introduction

The reduction of the beam pipe diameter in 1991 enabled the four large experiments at LEP to equip their detectors with silicon strip vertex detectors or to add an additional layer to the existing detector in the extra available space. Most of the vertex detectors have been upgraded several times to their final layout since then, increasing the angular acceptance needed for the LEP high-energy phase and following the progress in wafer production technology. The detector groups have accumulated substantial experience over the years concerning module and detector construction, reuse of old and integration of new components, operation in the experiments, environments and maintenance and detector repair.

2. The final LEP vertex detectors

The concepts of the final vertex detectors at LEP are briefly overviewed in the paragraphs below. Tables 1 and 2 compare main characteristics of the four detectors [1–10], and graphics of their layouts are shown in Fig. 1.

The ALEPH vertex detector [1,2] consists of 24 modules of 6 double-sided detector plaquettes each of which are arranged in two barrel layers. The same type of module is used both for the internal and external layer. Their pinwheel-like arrangement allows for an overlap with the neighbouring modules of about 5%. The readout is performed with the radiation hard version of the MX7 front end chip, AC coupled to the silicon via diode-protected capacitor chips located on the same hybrid at both ends of the module's. The z-strip readout is rerouted to the modules' ends by the means of polyimide fanouts in order to minimize the amount of material in the sensitive region. The

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Table 1
Characteristics of LEP vertex detectors

LEP experiments	ALEPH	DELPHI	L3	OPAL
Number of layers	2	3	2	2
Radii (cm)	6.3, 11.0	6.3, 8.9, 10.8	6.4, 7.9	6.1, 7.4
Modules/Layer	9, 15	24, 20, 24	12	12, 15
Detectors/Module	6	4, 8	4	5
Silicon length (cm)	39	28, 48	28	30
Min., max. $\|\cos\theta\|$	0.85, 0.95	0.91, 0.93	0.83, 0.93	0.89, 0.93
Modules overlap (%)	5	12–15	5	0
Channels	95 000	150 000	73 000	65 000
Front-end chips	MX7-RH	MX6, TRIPLEX	SVX-H3	MX7, MX7-RH
AC coupling	Capacitor chips	Integrated	Capacitor chips	Integrated
2-coord. readout	Double sided	Double + single	Double sided	Single sided
z readout	Polyimide fanout	Double metal	Kapton rerouting	Glass print
Readout pitch (μm)	$r\phi$: 50, z: 100	$r\phi$: 50, z: 44–176	$r\phi$: 50, z: 150, 200	$r\phi$: 50, z: 100
Material (χ_0)	1.5	2.7	0.4	1.5
Sensitive area (m^2)	0.96	1.37	0.52	0.53
Imp. par. res. (μm)	$r\phi$: 25, z: 25	$r\phi$: 20, z: 30	$r\phi$: 30, z: 30	$r\phi$: 18, z: 24
Prim. vtx. res. (μm)	x: 58, y: 10, z: 60	x: 22, y: 10, z: 22	x: 42, y: 10, z: 42	x: 40, y: 10, z: 85

Table 2
Characteristics of the DELPHI very forward tracker

DELPHI VFT	Pixel detector	Ministrip detector
Layers/End cap	2	2
Radii (cm)	6.9–8.4, 7.5–11.2	6.9–8.4
Inclination (°)	12, 32	50
Modules/Layer	38	12
Detectors/Module	1	2
Silicon size (cm^2)	$6.9 \times 1.7 \rightarrow 2.3$	5.3×5.3
$\|\cos\theta\|$	0.906–0.978	0.951–0.985
Modules overlap (%)	12, 37	15
Channels	1.2 million	24.500
Front-end chips	SP8	MX6
Coupling	DC	AC, integrated
2-coord. readout	Sparse data scan	Single sided back-to-back
Readout pitch (μm)	330 (pixel size)	200 (1 intermediate strip)
Sensitive area (m^2)	0.15	0.26

module's stability is ensured by a kevlar stiffener with a carbon fibre beam glued on top. The detector arrangement with its 40 cm long modules is mechanically strengthened with a hollow carbon fibre cylinder.

DELPHI's silicon tracker [3,4] is structured into the three-layer microstrip vertex detector in the central part and the Very Forward Tracker where two layers of ministrip and pixel detectors form the end caps of the tracker.

The barrel detector is built from 68 modules with up to 8 plaquettes in length, mounted in a staggered way which allows access to any module in a layer with either no or at most two neighbouring

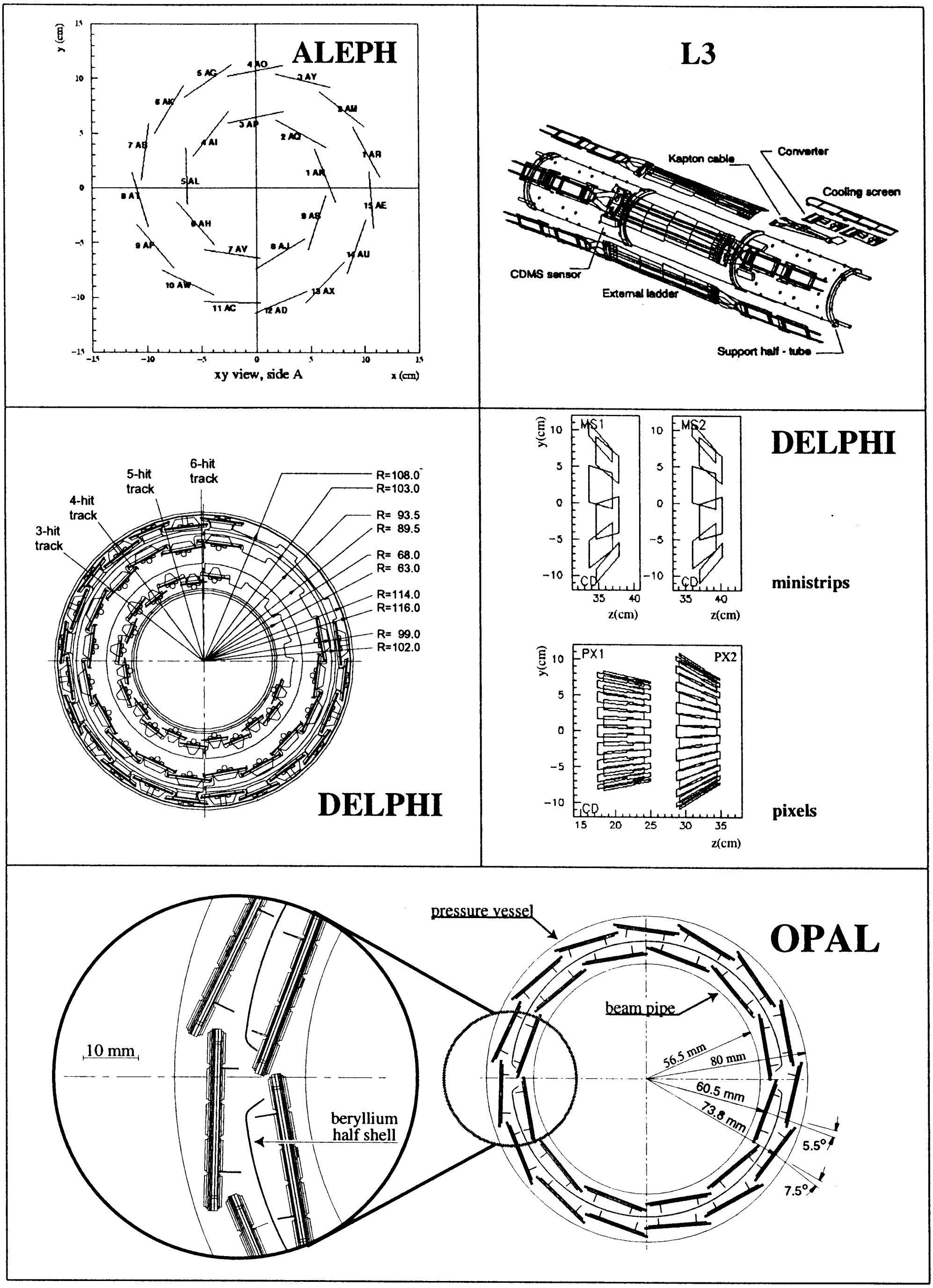

Fig. 1. Layouts of the LEP vertex detectors.

modules to be dismounted. Every layer has its own specific module type. The two internal layers are built from double sided detectors, whereas the external layer consists of back-to-back oriented single-sided plaquettes. The AC coupling as well as the z-strip readout via double metal are integrated in the detectors. The 152 pixel detector and 48 ministrip modules in the end caps are arranged in form of cones, inclined with respect to the beam axis and mounted on one side onto the aluminium support crowns.

A carbon honeycomb cylinder gives mechanical rigidity to the 56 cm long central detector; the shorter modules of the innermost microstrip and pixel detector layer are mounted on a composite adaptor piece which closely matches the thermal expansion of the barrel cylinder.

In order to allow an internal detector alignment, overlaps of the components and layers have been emphasized. The modules in the central part overlap by up to 15%; in the end caps the pixel detectors overlap by up to 37%. The innermost pixel cone reaches into the central region and provides a link from the central to the forward detector part. The total surface covered by sensitive silicon is $1.78\,\mathrm{m}^2$.

The vertex detector of the L3 experiment [5] is built from two radial layers of double sided microstrip detectors. The 12 modules per layer consist of 4 silicon plaquettes each, 2 per electrically independent half module, and are AC coupled via capacitor chips to front end chips SVX-H3 at both ends. The modules of the internal layer are parallel to the beam axis and mounted with 5% overlap serving the alignment. The modules of the external layer are tilted by 2° with respect to the beam direction, with the joint of the half modules being transposed. The aim of this design was to facilitate the pattern recognition.

The readout of the z-sensors is rerouted to the hybrids with special low-mass kapton cables of 0.02% radiation length, glued on top of the silicon plaquettes. A carbon honeycomb cylinder is integrated in the detector for reasons of mechanical stability.

The OPAL silicon strip microvertex detector [6] is built from 27 detector modules on two radial layers. They overlap slightly in order to use the available space best and to avoid dead regions between modules almost completely. The modules themselves consist of an odd number of back-to-back oriented detector pairs. Two and three pairs, respectively, of single-sided detectors form long and short ladders which are joined by an end support piece made of carbon fibre and beryllium pins, designed to minimize the gap in between the ladders. The two coordinate readout at the ends of the modules is achieved by rerouting the z-strip signals to MX7 front end chips via printed lines on glass substrate. The modules are fixed both on their hybrid side to water cooled end rings and with their intermediate connectors to the supporting beryllium cylinder.

3. Detector operation

3.1. Cooling

The power consumption of an entire detector is typically of the order of several hundred watts in a confined space. Therefore, the cooling of the front end and repeater electronics is essential for any detector operation and is carefully monitored. As soon as the detectors have been installed in the experiments and before their power is switched on, the cooling systems and related processes are started up to interlock the power supplies in case of temperatures exceeding predefined limits.

All vertex detectors at LEP are water cooled. The heat sources with microstrip detectors are well located at the modules' ends. About hundred mW are dissipated per front end chip and have to be removed from the hybrids. Temperature regulated water ($T \approx 20^\circ\mathrm{C}$, up to 16 l/min) is run through aluminium pipes machined in the end ring supports. Metal heat sinks in the hybrids provide good thermal contact. To avoid water leaks, the cooling systems are operated with slight underpressure, established either by pump or two-tank systems and siphoning. Separate circuits are usually set up for the different detector sides and sectors. During data taking conditions the temperature is kept stable to a few tenths of a degree. Power supply trips of parts of the detectors can result in local temperature gradients of several degrees.

Distributed heat dissipation occurs with the DELPHI pixel detectors where the front end chips cover the sensitive silicon completely. Even without draining the heat from the modules their temperature is limited by air convection and conduction through the ceramic support at the foot of the detectors. The modules warm up to about 30°C during operation, with a temperature gradient of 8°C along the structure [11].

The repeater cards and modules of the ALEPH vertex detector are provided with supplemental air cooling with a system designed to produce an air stream (150 m^3/h) of constant temperature and humidity despite seasonal variations of the ambient air.

3.2. Stability monitors

The short- and long-term geometrical stability of vertex detectors is important for the alignment and track reconstruction. The module shape is humidity and temperature sensitive. Especially, the kevlar supports turned out to bend with changing humidity by 50 to 100 μm. Carbon stiffeners improved the situation significantly. ALEPH further suppresses the influence of changes in humidity by blowing humidity regulated air into the detector volume.

Short-term movements of the order of 5–10 μm are observed especially with detectors which are periodically switched on and off.

Active and passive techniques have been developed to monitor detector movements online. With the ALEPH and L3 vertex detectors infrared laser spots are projected onto the silicon of the external layers. The induced signals are read out via the standard data acquisition system. Focussed light spots with 45° incident angle on the silicon provide sensitivity to radial movements of the detector plaquettes, whereas light spots shining perpendicular onto the plaquettes are used for monitoring transverse movements. Capacitive probes mounted on the L3 vertex detector are used for general checks. DELPHI surveys the geometrical stability with the overlapping detector regions. A simplified track finding has been included in online data quality checking program. Trace plots of residuals between tracks and hits in overlapping modules give information on the stability of the layers.

3.3. LEP related operation

Detectors with capacitor chips for the AC coupling of their strips have been found to be highly sensitive to radiation damage in case of beam losses. A solution to this problem was to use radiation hard versions of front end chips and capacitor chips which are diode-protected against overvoltages.

Further, protection is achieved by the introduction of LEP related states to the detector operation. ALEPH switches off both low and backplane voltages during LEP filling; the detector movements are measured and written to a database to be taken into account for the tracking (see Fig. 2). L3 and OPAL switch off or lower the depletion voltage during such periods.

DELPHI uses a LEP related detector state for the pixel detector in the Very Forward Tracker. A key characteristic of the pixel detector is the low hit occupancy and on-chip zero suppression. In high background situations however the number of fired detector elements increases. To protect from excess power consumption and the consequent tripping of the power supply system, the discriminator thresholds of the pixels are automatically raised to standby values outside LEP physics and lowered for physics again.

3.4. Data acquisition

With every minimum bias trigger the data acquisition systems read all microstrip channels. The analogue data stream is digitized and presented to

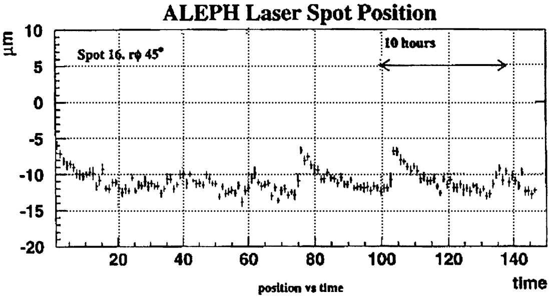

Fig. 2. Bending of modules of the ALEPH vertex detector during operation cycles.

signal processors for online filtering and data reduction. Signals from particle hits are identified and the charge spread patterns around the hits retained. Fastbus-based SIROCCO ADCs are used with the ALEPH, DELPHI and OPAL experiments. One ADC board usually handles the data from both sides of one or two detector half modules, depending on the number of readout channels per module. OPAL reads pairs of neighbouring half modules separately per side. The signal processor calculates online pedestals and noise for every readout channel and the common modes per chip by means of running averages. Clusters of strips around identified hits are output. Depending on the background situation the data suppression is between $\frac{1}{20}$ and $\frac{1}{200}$.

The L3 data reduction processor is VME based and identifies the channels' pedestals, noise and the chips' common modes prior to data taking from internally generated triggers. The algorithm applied for hit recognition achieves suppression factors between $\frac{1}{8}$ and $\frac{1}{10}$.

The pixel detector's data is filtered online during the Fastbus readout. Noisy pixels which respond to more than 1% of the triggers during prior calibration runs are written to masks which are applied at acquisition time. The number of masked pixels depends on the threshold settings. At nominal thresholds where the detector is maximally efficient approx. 0.3% of the pixels are affected (see Fig. 3). Calibration runs are performed after major changes of the detector settings and the masks updated. The quality of the suppression mask applied is surveyed with the detector's online monitor program. New pixels to be masked are identified and entered into a database. Their number increases in time as long as the permanent mask remains unchanged. The event size is reduced considerably by using masked pixel information. The zero-suppressed data from the pixel front-end electronics (data size already reduced to approx. $\frac{1}{330}$ is further reduced by factors of approx. $\frac{1}{60}$ during the readout and $\frac{1}{20}$ after the final masking.

3.5. Radiation monitors

Protection against extreme beam conditions as intense synchrotron radiation, very high ionisation due to beam losses near or localized in the silicon detectors and front-end electronics has been achieved by radiation monitor systems in the proximity of the vertex detectors. Sensors made from silicon diodes and solar cells measure continuously the radiation dose accumulated and trigger a beam dump when necessary. Passive thermoluminescent and radio photoluminescent devices mounted on some of the detectors provide an absolute calibration and can be accessed during maintenance periods.

ALEPH uses a rapid beam loss interlock system that is especially sensitive to spikes of low radiation doses [12]. Incidents have shown that the coupling capacitor chips can suffer from relatively low doses of below 1 rad, when the dose is received within miliseconds. Two sets of four photodiodes are read with an integration time of 100 μs. A signal to dump the fill is sent to LEP if thresholds exceed defined limits in a majority of the diodes.

DELPHI's radiation monitor [13] is designed to protect against high background integrating to a dangerous level. The limiting factor on the radiation sensitivity comes from the total dose acceptable for the detector electronics. The detectors themselves with integrated coupling capacitors are less sensitive to spikes of radiation. The monitor reacts on the time scale of tens of seconds. Counters are incremented depending on the background level and react fast to increases seen with single sensors. The information from four solar cells is combined to trigger warnings at several levels before dumping the beam.

L3 monitors the radiation dose online with twelve silicon diodes mounted circularly around the beam axis. The radiation dose is recorded continuously with gains from 3 mrad/h to 20 Mrad/h. A beam dump signal is issued with doses exceeding 0.6 rad/s for at least 300 μs on both sides of the detector.

OPAL measures the radiation dose from ionizing particles and synchrotron radiation with every beam crossing in a large dynamic range [14]. The sensors are made from the same wafers as the microstrip detectors. Fourteen radiation detector modules are mounted near to the front end electronics. They are exposed to the same level of radiation as the detectors of the internal microstrip

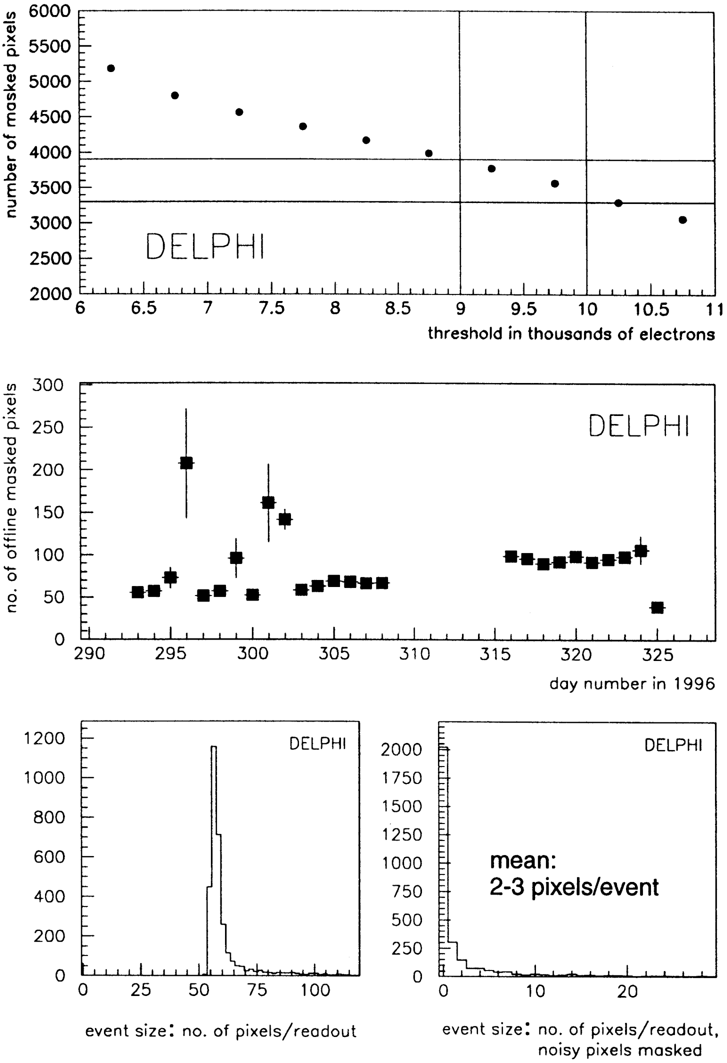

Fig. 3. Operation of the DELPHI pixel detector: (top) number of masked pixels as a function of the discriminator threshold; (middle) trace plot of pixels masked additionally offline versus time; (bottom) event sizes before and after final masking. Tails result from background with circulating beams.

layer. A solar cell based monitor serves as a backup and cross check system. The radiation monitor is able to trigger a beam dump in less than 1 ms.

4. Maintenance

During the yearly shutdown periods it is usually possible to access the internal parts of the experiments. Maintenance of vertex detectors is a complex operation. It involves extraction and insertion of the entire structure with cables, cooling tubes and the beam pipe in place. Little clearance between detectors and various support components means a high potential of danger for damage to the silicon sensors. The dismounting and re-assembly of the various detector parts after the transport to laboratory rooms is a highly demanding procedure for the detector team. Experts for the different tasks have to be available as well as spare parts prepared.

Components are often not designed to be removed and put back in place several times. They might be in extreme proximity to other sensitive parts of the system so that interventions may risk more damage than repair. Unforeseen delays with respect to the imposed time schedule are possible. Comprehensive functionality tests after every step of mounting, installation and closing of the experiments are essential for a working detector system. The experiments consider the following general criteria for a necessary detector extraction and repair.

ALEPH sets a lower limit at about 2% of channels failing. 0.5% of channels, i.e. one-half module, is known to be not working currently. DELPHI is discussing the impact of module failures on physics measurements. Especially the innermost and external barrel layers are important, and more than one module has to fail there before intervention will take place. In any case the risk for the other subdetectors has to be considered.

L3 will take the vertex detector out with one or two modules failing completely. OPAL did not extract its vertex detector during the shut down 1996/97. All modules performed well during LEP physics periods. Two modules failing on the $r\phi$ side in 1997 represent 1.7% of the solid angle. Only one layer is affected. No intervention is foreseen for the coming maintenance period.

5. Conclusion

Since 1990/91 silicon strip vertex detectors are integrated into the four large experiments at LEP. Experience has been gained on various technological items as sensor design, bonding, glueing, mechanics, cables, cooling, slow control and data acquisition. The production of the modules has been possible only in close contact with industry and international collaboration with partner institutes. Most of the detectors have been upgraded and repaired every year to replace or include new components. Novel experience has been gained on how to operate active pixel detectors in a collider experiment.

The vertex detectors are integrated in the experiments track reconstruction and contributed successfully to the physics program at LEP by providing precision measurements (e.g. Ref. [7–10]).

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