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Measurements of LEP II beam parameters and background using VSAT calorimeter - the smallest and closest to the beam sub-detector of DELPHI.

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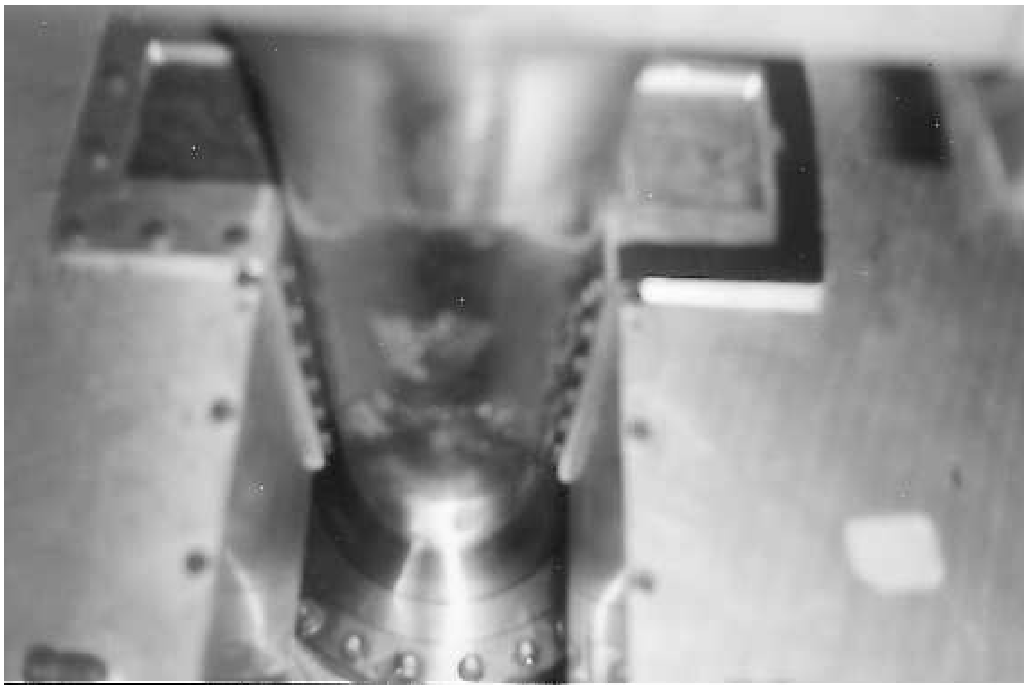

Theses submitted for the Degree of Filosofie Licentiat

Abstract

The VSAT (Very Small Angle Tagger), sub-detector of the DELPHI (Detector with Electron, Photon and Hadron Identification) experimental setup, was created jointly by the Milano-Torino-Trieste-Lund team in order to provide precise on- and off-line luminosity monitoring based on the Bhabha events rate. VSAT was also used to provide tracking information for leptons from gamma-gamma (two photon) physics events as another important feature. This latter feature became the most important one during the last years of DELPHI data-taking because the STIC (former SAT) luminosity monitor could provide (after upgrade) a much better absolute luminosity precision than the VSAT.

The VSAT detector is sensitive to the LEP beam parameters and those were calculated for the geometry of LEP II. Beam parameters for 1998, 1999 and 2000 are presented.

During two years I was in charge of the data-taking and slow control of the VSAT calorimeter and of checking the data quality, and also of the off-line primary processing and storage of VSAT data. The last two years of operation, and problems connected with the LEP II beam configuration and DELPHI trigger system, are discussed.

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Chapter 1

Introduction

1.1 Overview and scientific goals

The main purpose of the LEP (Large Electron Positron) collider was the study of e^+e^- collision in the new energy range, producing the mediators of the weak force W^{+-} and Z^0. The Z^0, and its charged partners the W^{+-}, were both discovered at CERN in 1983. In order to do that study the production and decays of the weak mediators in detail one needs not only a first class collider but also a good experimental setup (detector like DELPHI). The LEP collider's initial energy was chosen to be around 91 GeV, so that Z^0 particles would be produced (LEP I phase). In order to produce pairs of W^{+-} the energy requirement was more than 163 GeV (LEP II phase). Then in order to search for Higgs the energy was increased in steps up to 208 GeV in centre of mass system.

Other primary experimental goals of LEP were to provide thorough tests of the Standard Model, precise QCD analysis, and possibility to investigate the problem of Higgs - a hypothetical particle, associated with the electroweak symmetry breaking mechanism, which is required to make the W^{+-} and Z^0 bosons massive.

1.2 LEP collider

Studies of the design of the LEP machines started at CERN in 1976 and the first practical design was published in 1978. This machine design had a cost-optimised energy of 70 GeV per beam and measured 22 km in circumference. After extensive discussions during the autumn of 1978 it was decided to embark on the design of a somewhat larger machine, 30 km in circumference, with a cost-optimised energy of about 90 GeV per beam. The energy of both these machines could be extended, by using super-conducting RF cavities, when these become available, to 100 and 130 GeV respectively. One finally settled for 27 km circumference which limited the energy to 105 GeV per beam, for a short time at autumn of 2000.

The early development of the Large Electron-Positron storage ring (LEP) project is best described by John Adams in his Annual Reports to the CERN Council in 1979 and 1980. The operation of the LEP collider started in August 1989.

For a time-mark one can stress on two dates: first injection into the LEP collider took place on 14 July 1989, one day earlier than scheduled, and first collisions of electrons and positrons were provided almost exactly one month later, on 13 August 1989.

The construction took about 8 years. LEP is the biggest accelerator ever built in the world, having a 26.67 km Main Ring tunnel. The tunnel itself represented less than half of the 1.4 million of cubic meters of material which had to be excavated for the project. The remainder of the underground work consisted of the four experimental caverns (the homes of DELPHI, OPAL, ALEPH and L3 experimental setups), 18 pits, 3 km of secondary tunnel, and some 60 chambers and alcoves. After an extensive campaign of test drilling in and around the area proposed for the LEP tunnel it was decided to incline the plane of the tunnel by 1.4 %. This decision was made so as to ensure that all underground caverns and the main part of the tunnel would be located in solid rock while, at the same time, limiting the maximum depth of the shafts to less than 150 m. The solid rock provided a stable base for magnets and vacuum beampipe itself and too long shafts might be dangerous in case of emergency situation underground (fire, explosion, flooding).

In addition to the underground civil-engineering work, the construction of LEP necessitated the construction of 71 surface buildings of a total area of some 51000 square meters, situated over eight sites.

The bending field of dipoles has been made unusually low (about 0.225 T for 100 GeV beams) so as to increase the bending radius and thereby reduce the amount of synchrotron radiation. The current in main dipoles is 4200 A at 94.5 GeV and the current in main quadruples is 400 A at 94.5 GeV.

The strength of all magnets in the LEP ring are very accurately adjusted by controlling the current flowing in their coils. This is accomplished by the use of more than 750 precisely stabilised DC power supplies ranging from less than 1 kW to a maximum of 7 MW. The specifications for these power supplies are extremely tight, both individually and, during energy ramping, in their synchronisation. For the main dipole and quadruple supplies, absolute accuracies down to 2 parts in 10^5 have been achieved with a resolution typically three times better.

Each magnet has, of course, its own cooling circuit. For the majority, the cooling is provided by demineralised water circuites, which are connected to a total of 10 cooling towers with a capacity of 10 MW each. Some of the small corrector magnets are air-cooled, whilst the super-conducting quadruples and the super-conducting experimental solenoids are cooled by liquid helium at 4.2 K from the cryogenics installation.

As of 1998 the super-conducting system consists of 272 cavities. 4 cavities make one module with 1 klystron drives 2 modules and can deliver 1 MW RF power. The modules are made by: Circa (France), Ansolda (Italy) and Siemans (Germany).

LEP was upgraded to LEP II during 1996 by using super-conducting RF cavities covered with niobium with a field gradient of up to 7 MV/m. LEP II has reached 206-208 GeV collision energy by the end of the operation (November 2000) in spite of the initial plans where the limit of the LEP energy who though to be around 91 GeV. This was archived by improving the quality of the surface in the cavities and due to improved cooling.

At 94.5 GeV a particle would loose 2.33 GeV per turn to synchrotron radiation. If this weren't replaced the particle would rapidly spiral into the beam pipe. At 94.5 GeV a total accelerating voltage of 2700 MV is provided by the RF system.

Four different detectors have been constructed to collect data on electron-positron collisions: ALEPH, DELPHI, L3 and OPAL. Sweden participates (Lund University, Stockholm University and Uppsala University) in one of these detector collaborations, e.g. DELPHI which will be discussed further.

LEP took electrons and positrons from the SPS at 22 GeV, and, in 1998, accelerated them up to 94.5 GeV. At the end of year 2000 the 101.0 to 104.5 GeV were typical energies but the adjustment periods were much more longer and difficult in comparison with energies below 101 GeV. The mini-ramp system (i.e. increasing energy in small, 0.5 GeV steps as the beams intensity decreases) for climbing up the energy was proposed and used. Beams at maximum energy were quite unstable and the intensity was low.

At an energy of 22 GeV: $\gamma = 43052.8$ v/c = 0.999999999730247
$c - v = 0.080926$ m/s and in a week that's only 48944.00 meters.
At an energy of 94.5 GeV: $\gamma = 184932$ v/c = 0.999999999985380
$c - v = 0.004386$ m/s and in a week that's only 2652.67 meters.

You can call it acceleration but you can see that the beams don't actually pick up much speed!

The duration of a typical run with particles for a physics fill is 12 hours for 45 GeV energy per beam. During this time each of the 10^{12} particles in the beams will have traversed the complete 26.67 km of the LEP vacuum chamber about 500 million times. In order to minimise particle losses due to collisions with residual gas molecules, the whole vacuum chamber must be pumped down to very low pressures. The achieved static pressure for LEP is 10^{-12} or 10^{-11} Tor whereas in the presence of beam the pressure rises to about 10^{-9} Tor. This pressure rise is due to gas evaporation from the inner vacuum-chamber wall, provoked by the synchrotron radiation of the circulating beam, and has had a profound influence on the design of the LEP vacuum system.

The two main components of the vacuum system are the vacuum chamber itself and the pumping system. Of the 27 km of LEP vacuum chamber, a length of about 22 km passes through the dipole and quadruple magnets, and is subjected to the heating due to synchrotron radiation. Although this heating represents a mere 100 W/m for the LEP I period phase, it rises to more than 2000 W/m during LEP II period (1997-2000). Therefore the chambers need water-cooling channels and are constructed from aluminium because of its good thermal conductivity. However, only about half the radiated power would be absorbed by the aluminium; the remainder would normally escape into the tunnel and produce such a high radiation dose that organic materials such as gaskets, cables, electronic components, etc., would be rapidly destroyed. In addition, severe damage could result from the formation of ozone and nitric oxides, which produce highly corrosive nitric acid in the presence of humid air. For these reasons, the aluminium chamber is covered with a lead cladding of a thickness varying between 3 and 8 mm, which greatly reduces the radiation that escape into the tunnel during operation.

For reasons of reliability the 26.7 km of the LEP vacuum beampipe is subdivided into smaller 'vacuum sectors' with a maximum length of 474 m. During shutdown periods, when there is no circulating beam and work is often going on in the tunnel, these vacuum sectors are isolated from each other by full-aperture gate vacuum 'sector valves'. So, if an accident occurs, only 474 m of vacuum will be affected and not the full 26.7 km.

The beam size depends on where in the ring you look. At the interaction point where the beams collide the vertical beam size is 3 to 4 microns, and the horizontal beam size is 190 microns (0.19 mm). More typically, in the other places, the beam size is 4 mm horizontally and less than 1 mm vertically. VSAT can also provide some information about beam size in the DELPHI Interaction Point (Table 1.1) but one should be aware that information from VD (Vertex Detector) is more precise since VD is close to the IP, has better angular resolution and geometrical acceptance.

Table 1.1: Beam dimensions at DELPHI IP by VSAT

	period	typical values:	eps(nm)	beta(mm)	sigma(mcm)
	LEP1:	x	35	2.5	296
		y	0.7	0.05	5.9

The bunch length at 94.5 GeV is about 2 cm (2 σ drop of electron density). 6 mA total beam current is around $3.34 \cdot 10^{12}$ particles. The energy lost per turn at 94.5 GeV is 2.33 GeV. Considering the beam current mentioned above around 14 MW RF power taken by the beam. The system runs at around 352 MHz (wavelength 85 cm). At high energy the total energy request is about 130 MW with approximate cost around 5500 CHF/hour.

The energy consumption for each subsystems is: Super-conducting RF: 39 MW, Copper RF: 20 MW, Cryogenics: 8 MW, Magnets: 22 MW, Water cooling: 5 MW, L3's solenoid: 4.5 MW, Other: 30 MW.

For the whole CERN when all accelerators are running (PS, SPS and LEP), the energy consumption is 250 MW and the approximate cost is 12000 CHF/hour

During 10 years of work the LEP luminosity was increasing steady (Fig. 1.1) but one should take into account that luminosity for smaller energies like 45 GeV per beam is always better then for higher energies no matter which kind of upgrades were made. In spite of careful checks and precise guidance of the beams the four LEP experiments (ALEPH, DELPHI, OPAL, L3) nearly always received a different differential (and as a following a different integral) luminosity - the fact which makes some of the collaboration happy and some just opposite.

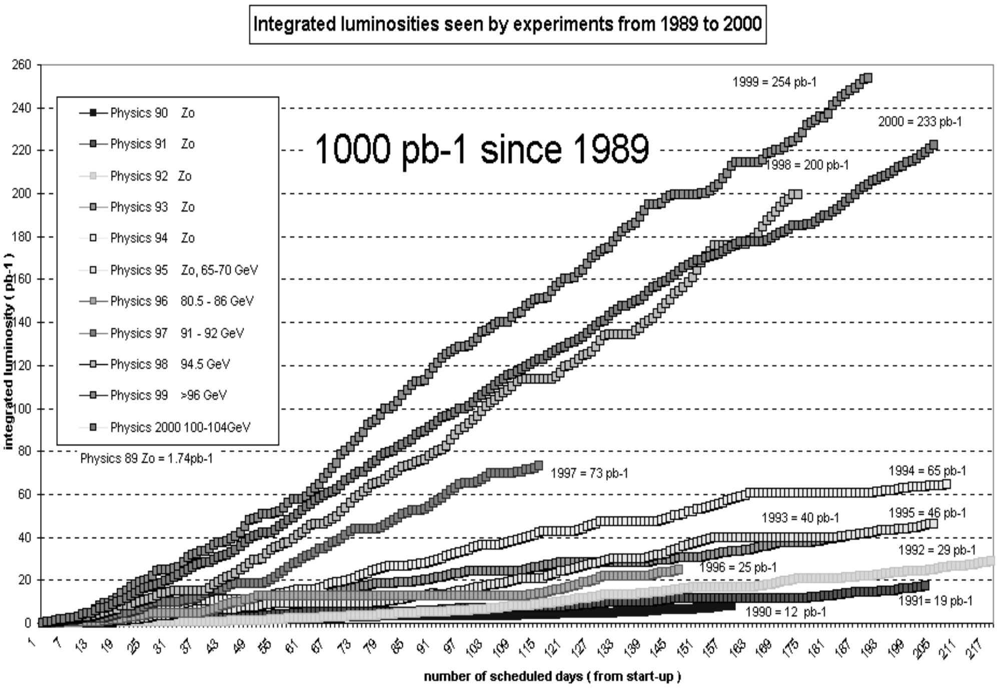

Figure 1.1: Integrated luminosity seen by experiments from LEP

LEP has provided 8984 physics fills. One fill means one cycle of collider operation which consists of injection, acceleration, adjustment and beams collision until beams are lost or got dumped because of small intensity.

1.3 DELPHI detector setup

The DELPHI detector came into operation in 1989, and since than it collected experimental data for the consequent physical analysis. Electron-positron annihilation has been studied for various centre-of-mass energies : at the Z^0 boson peak (91.2 GeV) in 1989-1995, 130-136 GeV in November 1996, 161 GeV in July/August 1996, 172 GeV in October/November 1996 and 183 GeV since 1997, 200 GeV since 1999 and from 200 GeV to 208 GeV during the last year 2000.

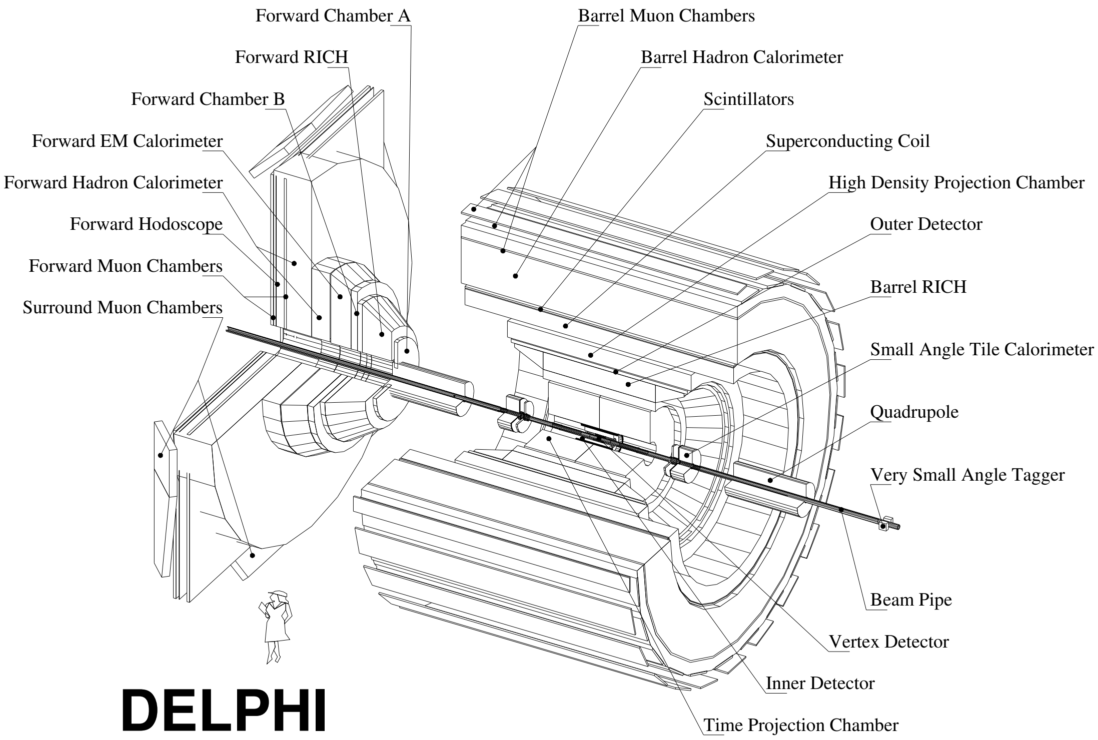

Figure 1.2: View of DELPHI barrel and one end-cup which is separate from barrel with the couple of VSAT modules on the right

DELPHI (DEtector with Lepton, Photon and Hadron Identification) is a general purpose detector for e^+e^- physics at LEP on and above the Z0, offering three-dimensional information on curvature and energy deposition with fine spatial granularity as well as identification of leptons and hadrons over most of the solid angle. It has been operating since 1989. The detector is installed in a cavern 100 meters below ground. Actually it's the lowest point of LEP tunnel and the place is well below Geneva lake too.

DELPHI detector consists of a cylindrical section (the barrel), covered with two end-caps. A super-conducting solenoid provides a 1.23 T solenoidal field of high uniformity parallel to the beam axis in the volume containing barrel tracking detectors. Tracking relies on the Vertex Detector, the Inner Detector, the Time Projection Chamber, the Outer Detector and forward drift chambers. Electromagnetic showers are measured in the barrel with high granularity by the High Density Projection Chamber, and in the end-caps by the Forward Electromagnetic Calorimeter. The smaller polar angles, essential for detecting electrons and positrons from two-photon processes and for luminosity measurements, were covered until 1994 by the Small Angle Tagger and the Very Small Angle Tagger. Later SAT was replaced with the Small angle TIle Calorimeter.

In addition, scintillator systems are implemented in the barrel and forward regions for triggering purposes and in order to achieve complete hermeticity for high energy photon detection. The iron return yoke of the magnet is instrumented with limited streamer mode detectors to create the Hadron Calorimeter which serves also as filter for muons, which are identified in two drift chamber layers. In 1994 a layer of Surrounding Muon Chambers was installed outside the end-caps to fill the gap between the barrel and forward regions.

Charged particle identification is provided mainly by complicated liquid and gas Ring Imaging Cherenkov Counters both in barrel and forward regions.

1.4 VSAT

The VSAT (Very Small Angle Tagger - [3]) detector is the one of three DELPHI subdetectors which are able to provide beam related information. The other two are VD (Vertex Detector around interaction point) and STIC (Silicon TIle Calorimeter by each end of the barrel). VSAT is the most sensitive one since its position is very close to beam and therefore the measurements are strongly affected by the background and beams distortions. Precise results can be accomplished because the statistics is high enough. The VSAT modules are quite far away from the interaction point (IP) and mainly counting Bhabhas with θ angle around 4 - 7 milliradians (ϕ angle within $+-50^o$). VSAT consists of four identical modules with 3x5 cm sensitive area. They are placed as two pairs of modules each 7.7 meters from interaction point (IP) with two quadruple magnets around IP between couples of VSAT modules Fig. 1.3.

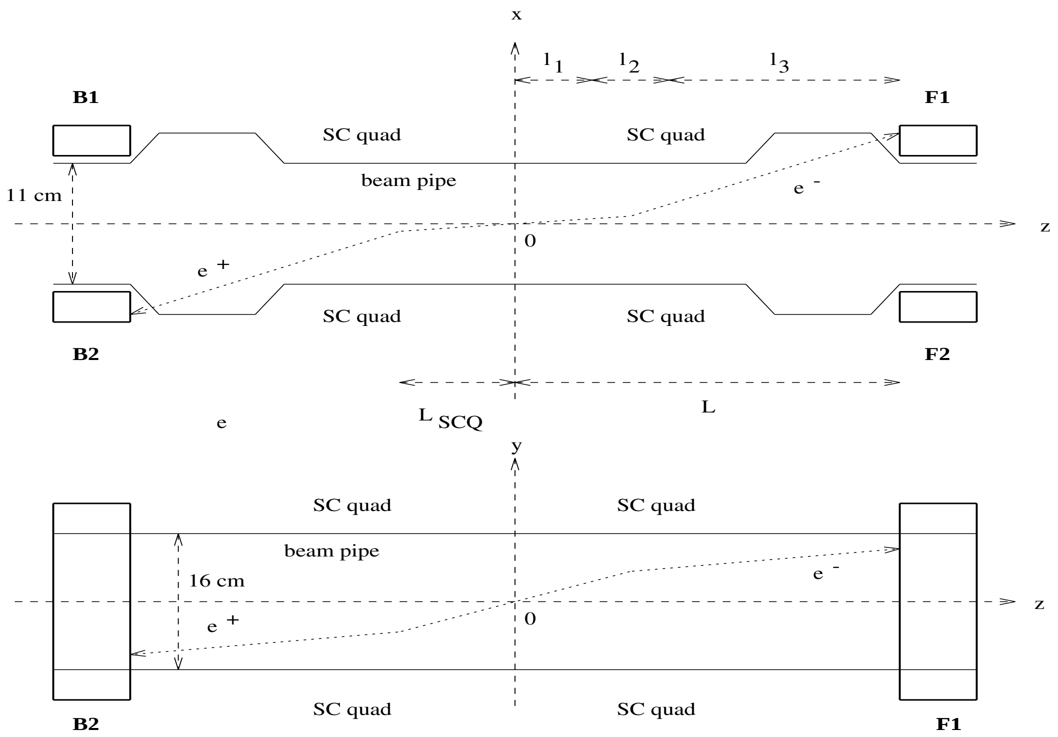

Figure 1.3: Crosscuts of VSAT modules positions in horizontal (up) and vertical (down) planes. The distances given: L=7.7 m, L_{SCQ}=3.7 (from IP to the quadruple centre), l_2=2.0 m - length of quadruple, l_1=2.7 m, l_3=3.0 m.

Each detector module (they called 1,2,3,4 or B1,B2,F2,F1) is a sandwich calorimeter (as shown in the Fig. 1.4) made by tungsten absorber and silicon detectors. There are 11 silicon diodes or FADs (Full Area Detectors) planes and three strip planes (two for X and one for Y axis).

Both kinds of silicon detectors have a thickness of 300 μm (0.3 mm). All FADs are separated by tungsten absorbers with size 5.12 cm x 5 cm and two radiation length thickness (0.38 cm). The FADs have a full depletion voltage of around -30 V (operational voltage around -25 V) with capacitance 500 pF. A lead dump installed behind the last FAD plane in order to stop a background from backward moving off-momentum leptons.

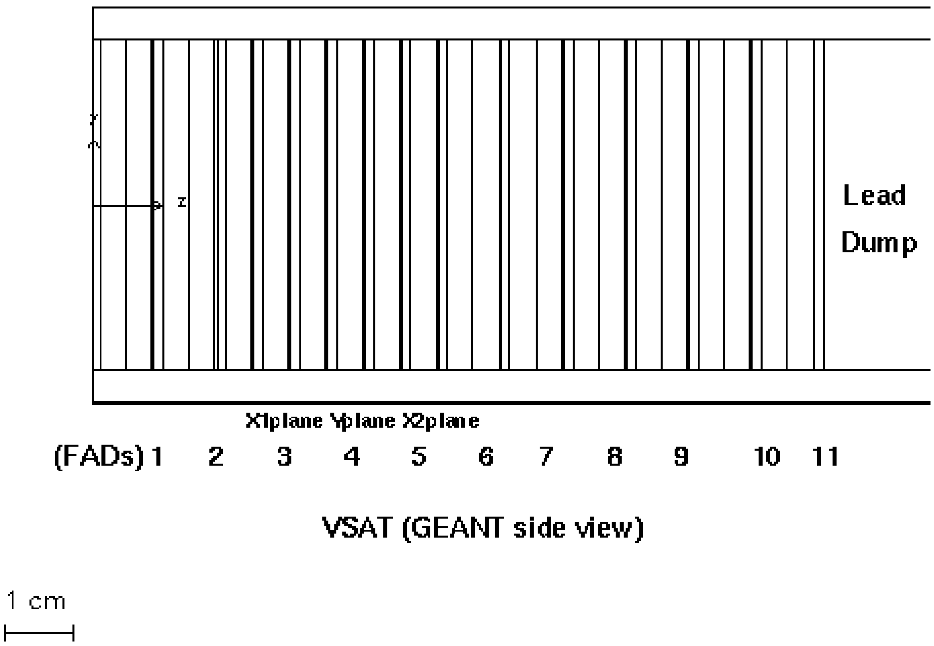

Figure 1.4: Side view on internal composition of VSAT module (made by interactive shell of GEANT 3.21 program)

The three silicon strip planes called X1, Y, X2 are 5x5 cm^2 in size with 1 mm pitch and placed at 5,7,9 radiation length into the modules and are used for the (X,Y) shower position measurement. There are two planes for the X measurement with 32 strips (each strip 1 mm wide, 50 mm high) and one for the Y measurement with 48 strips (each strip 50 mm wide, 1 mm high). Full depletion and operation voltages are equal +25 V for both types of strip planes.

The distance from beam centre to the modules is about 5.7-5.9 cm after the LEP II upgrade (end of 1997) of the beam tube. The idea was to bring detector modules as close as possible to the beams in order to increase the electron-positron acceptance for gamma-gamma physics. Their displacement by this coordinate is not absolutely symmetrical. Basically, the position of the VSAT modules are defined by the shape of the beam-pipe section (Fig. 1.5).

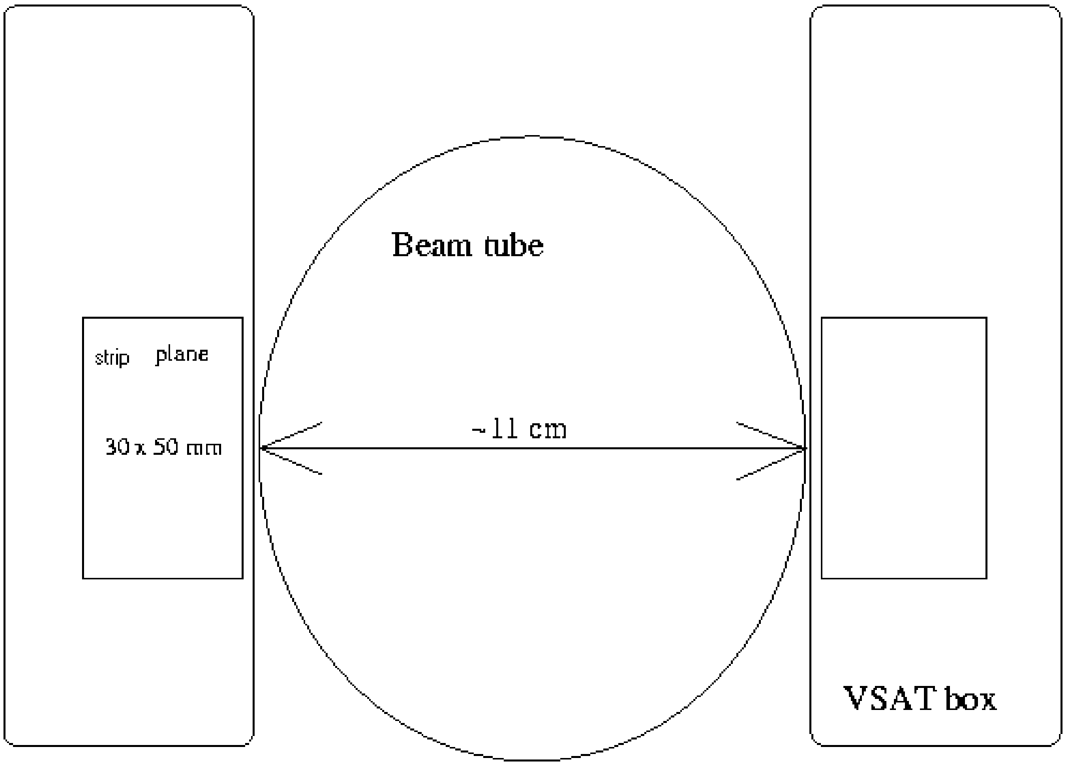

Figure 1.5: Crosscuts of VSAT modules pair with beampipe

The change of position increases the acceptance of each module in different ways.

Table 1.2: Position of VSAT modules

$Years$:	Description	LUM1(B2)	LUM2(B1)	LUM3(F2)	LUM4(F1)
$1994 - 97$	geometry	Mod 1	Mod 2	Mod 3	Mod 4
	DATA XXIN94	-6.386 cm	6.178 cm	-6.343 cm	6.219 cm
	DATA YYLO94	-1.677 cm	-1.675 cm	-2.231 cm	-2.335 cm
	DATA ZZFR94	-776.0 cm	-775.8 cm	775.9 cm	775.8 cm
$1998 - 00$	geometry	Mod 1	Mod 2	Mod 3	Mod 4
	DATA XXIN98	-5.728 cm	5.915 cm	-5.915 cm	5.800 cm
	DATA YYLO98	-2.399 cm	-2.245 cm	-2.245 cm	-2.377 cm
	DATA ZZFR98	-776.10 cm	-776.07 cm	776.07 cm	775.55 cm
$1998 - 00$	Bhabha acceptance	Mod 1	Mod 2	Mod 3	Mod 4
	DATA XBIN98	-5.78 cm	5.96 cm	-5.97 cm	5.85 cm
	DATA YBLO98	-2.35 cm	-2.19 cm	-2.20 cm	-2.33 cm

It should be mentioned that events which have a maximum of transversal shower profile in the 1st X strip (so-called first strip hit or strip error) always have been thrown out from off-line reprocessing since this measurements requires data from the two neighbouring strips to the strip with the biggest signal in order to extract an accurate position of the shower maximum - if the 1st strip has the largest signal then leakage correction of the energy is impossible. The instrumental acceptance coordinates is 0.5 mm shorter for X than is shown in Table 1.2.

All DELPHI sub-detectors, e.g. the VSAT, has it's own homepage at DELPHI sub-detectors description page:
http://delphiwww.cern.ch/ offline/physics/delphi-detector.html

Chapter 2

Experience of VSAT operation during 1999-2000

2.1 MIG scalers for on-line background and luminosity monitoring

The VSAT is the only sub-detector in DELPHI which is capable to provide on-line background and luminosity during filling, acceleration and adjusting of the beams. This feature was based on the direct connection from VSAT Local Trigger Superwiser (LTS) electronic unit to the DELPHI scaler's logical box and processors. VSAT signals were processed there among other important direct signals from DELPHI sub-detectors affected by beam parameters and background.

The data from the LTS provided signals to so-called MIG scalers: Bhabha counters - integral (per fill) and differential (per second) number of Bhabha hits in each diagonal, False Bhabha (FB) counters - integral and differential number of coincidences in both diagonals, Single Electrons (SE) counters - integral and differential number of single hits in each of the four VSAT modules. Before LEP II phase the False Bhabha counters were abandoned since DELPHI cannot afford to wait 3 minibunch periods 22 microseconds each for such a coincidence with the improved collision rate of LEP II (dead time became too long). However the False Bhabhas rate could be calculated off-line from the Single Electrons rates.

Using the Single Electrons one can calculate the instant background by making a sum of Single Electrons counters - so called Background 2 from DELPHI or off-momentum electron background. The approach to measure an instant luminosity is a little bit more complicated.

$$L = \frac{(Bhabha14 + Bhabha23) - (SE1 \cdot SE4 + SE2 \cdot SE3)}{\sigma(500nb)} \tag{2.1}$$

Where $Bhabha14$ and $Bhabha23$ are the Bhabha counters and $SE1 - 4$ are the Single Electron counters. Apart of MIG scalers as numbers the Data Acquisition operator (DAS Maestro and shift leader) of DELPHI received a traceplot of background and luminosity. These traceplots helped a lot in defining the right time for the collimators to be closed (opened) and for the start of data-taking.

2.2 Luminosity measurements and Bhabha scattering

To monitor luminosity the VSAT used Bhabha scattering. The integral luminosity is defined as:

$$\int L dt = \frac{N_X}{\sigma_x} \tag{2.2}$$

there is N_x is the number of events produced in any reaction X, and σ_X is the known cross-section for that process. A high precision measurement of the luminosity therefore allows the accurate determination of absolute cross sections of other processes from their rate. Because of its large cross-section, especially at small angles, Bhabha scattering ($e^+e^- -> e^+e^-$) is very useful for determining the luminosity. The theoretical cross-section has to be known with high accuracy. At LEP energies, the contribution to the cross-section from weak and higher order effects is non-negligible, and lowest order QED calculation does not suffice, but those effects have been calculated with good accuracy.

In pure QED, Bhabha scattering can to lowest order be visualised by the two Feynman diagrams like: the leptons interact by exchanging either a space-like or a time-like photon propagator. At small angles the latter graph dominates, the centre-of-mass differential cross-section for high energies so that electron mass can be neglected is easily calculated and is found to be:

$$\frac{d\sigma_0^{QED}}{d\Omega} = \frac{\alpha^2}{4s}((1+c^2) + 2\frac{(1+c)^2+4}{(1-c)^2} - 2\frac{(1+c)^2}{1-c}) \tag{2.3}$$

where $c = \cos\theta$. Here s is the centre-of-mass energy squared and $d\Omega$ is the solid angle element $d\cos\theta\ d\phi$. The angles θ and ϕ are defined as the polar and azimuthal scattering angles of the positron. The three terms in the equation correspond to the annihilation diagram (s channel),the exchange diagram (t channel), and the interference term (between both of them), respectively. For small scattering angles (θ less than 1), it is seen that the exchange term will dominate; it has a pole for $\theta = 0$ corresponding to the infinite range of the Coulomb potential.

For practical calculation Equation 2.3 can be reduced to the simpler form:

$$\frac{d\sigma_0^{QED}}{d\Omega} = \frac{\alpha^2}{4s}(\frac{3+c^2}{1-c})^2 \tag{2.4}$$

For θ less than 1, it is found, that

$$\frac{d\sigma_0^{QED}}{d\Omega} \approx \frac{16\alpha^2}{s}\frac{1}{\theta^4} \tag{2.5}$$

from which the forward peaking of the cross-section is clearly exposed.

2.3 Two photon (gamma-gamma) physics

When electrons and positrons interact in LEP they radiate photons at small angles relative to the beam axis (parallel to the beams). This is the source of two-photon collisions (Fig. 2.1), producing a hadronic state X according to $e^+e^- -> e^+e^-X$. While for a given beam energy the e^+e^- kinematics of an annihilation process is fixed, the continuous spectra of the photons will allow simultaneous measurements at different $\gamma\gamma$ invariant masses and for different momentum transfers.

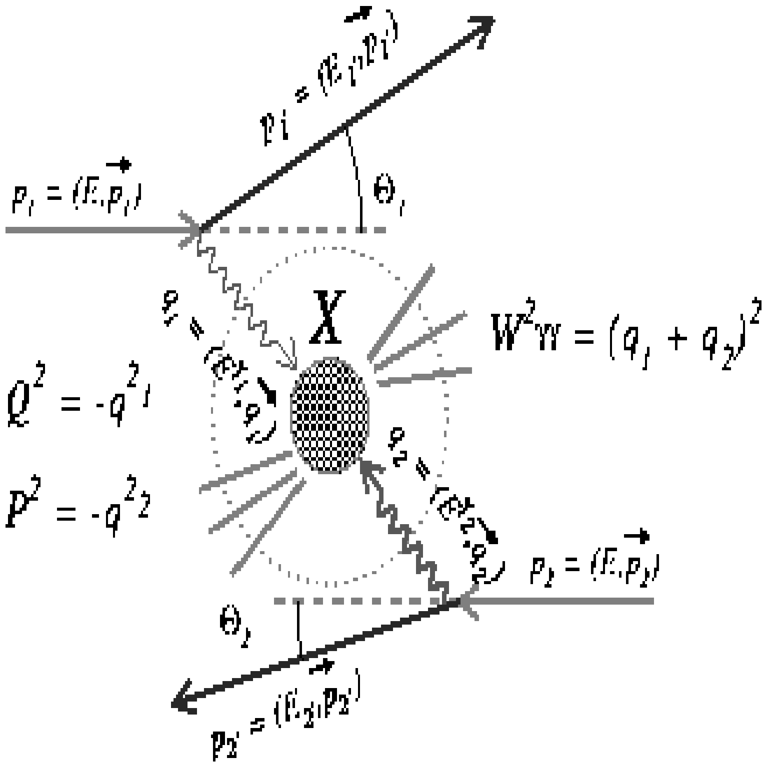

Figure 2.1: Feyman diagram for two photons collision

The electron-photon vertices are pure QED processes and therefore exactly calculable. The main interest lies instead in studying the photon-hadron coupling, i.e. the interaction between photons and quarks.

For two-photon events with high momentum transfer this coupling is best described by the Quark Parton Model (QPM), where the photons have a point-like coupling to a quark which subsequently fragments into hadrons.

For smaller momentum transfers the Vector meson Dominance Model (VDM) works better. Here the photons transform into virtual vector mesons, which then interact through the strong force, showing characteristics of soft hadron interactions. Events with medium P_t multi-jet production can be described by a QCD-based model of the hard scattering of the photon's hadronic constituents, thus implicitly needing a gluon component in the photon. The analysis procedure assumes smooth transitions between these different models.

It is possible to use forward electromagnetic calorimeters for tagging one or both of the outgoing electrons for two-photon reactions. The VSAT had been used for this purpose since taggers situated in the very forward regions of DELPHI have the highest cross-section for two-photon events. By studying double tag events in the VSAT, where both leptons were measured, it is possible to fully determine the momentum carried by the photons, thereby getting a precise measurement of the invariant mass of the hadronic system. Analysis of double tag events in the VSAT using LEP II data are soon to be published in a PhD thesis by Andreas Nygren.

For the future one can also combine STIC and VSAT as taggers for two-photon events to reach higher virtuality of the photons. I plan to study the data and investigate this method together with Nikolai Zimin and Sverker Almehed.

2.4 Examples of problems in DELPHI

During two years of work in DELPHI then I was in charge of the VSAT detector operation I have visited an lot of so called pit meetings which used to be Monday, Wednesday and Friday at 16:00. The pit meetings period started before actual data-taking starts and usually tended to finish a couple of weeks after LEP went to shutdown mode for the winter.

The main purpose of these meetings was to solve the problems which happened with sub-detectors, Slow Control, Data Acquisition and Data Quality of DELPHI in general. A lot of useful things was learned from sub-detector's teams and responsible persons. The discussion with all active parts of DELPHI collaboration itself could help more than an hours of desperate attempts of individual repair work, not to mention the kind help from other members of DELPHI data-taking team.

The problems we met can be divided in technical (in and outside DELPHI) and human errors. Both types of problems tend to grow closer to the end of the data-taking period since detector's hardware develop faults and many people who were creators of sub-detectors and sub-systems (and knew it by heart) were retired, had moved to other positions and experiments (sometimes very far away).

A common DELPHI problems was some dying lamps in the barracks or even in LEP tunnel and galleries. They sometimes produced such a huge radio noise that part of the whole DELPHI could be out of real data-taking until the lamp was switched off.

The instabilities in power supply (i.e. voltage drift and noise) tended to produced another similar level of disaster for the whole of DELPHI or some of the counting barracks. A lot of action was taken including special monitoring program running permanently on a PC in the DELPHI Control room.

Another problem happened during last summer. The main workhorse of the triggering system - Pandora timing and synchronisation boards for FastBus crates became de-synchronised rapidly (in 2-3 days) for the most part of sub-detectors using this kind of board (around 2/3 of DELPHI actually).

For the same operational problems it is better to describe sub-detectors of the DELPHI, using groups of them according to the tasks they were designed for:

2.4.1 1st group - Tracking

Silicon Tracker : Vertex Detector (VD) and Very Forward Tracker (VFT)

The Vertex Detector (VD) consisted originally of a barrel with two layers of microstrip detectors in the beginning of DELPHI. Later it was upgraded by adding a third layer to the barrel and cone side panels made from pixel detector planes for small θ angles (so called Very Forward Tracker). The pixels needed to be configured properly before physics started. They produced a main VD difficulty. One part of this problem is hardware (in form of noisy and dead blocks of pixels which were supposed to be masked), and another part of it is software (in form of not properly loaded thresholds, buffers and masks for pixels).

Apart of these problems VD had a problem with temperature reading (dead probe), cooling (provided by nitrogen gas) which lead to a small deformation of the layers (in order of millimeter). The track information was used to calculate the shift of layers and monitor the change of that shift.

It should also be mentioned that the radiation dose absorbed by the VD was always closely watched by shifters and several times during DELPHI life the LEP beams were dumped because of high radiation flux in the VD region and risk of damaging the sensitive layers.

Inner Detector : ID

The Inner Detector made from straw tubes, experienced a lot of problems with background in form of trips (i.e. the sparks between cathodes and anodes which lead to shortcuts and switching off the voltage). Ramping up the voltage after such a trip was a tricky task especially if the background level is still high. It was decided for that if more than 5 straw tubes experienced the trip the whole detector should be switched off and then ramped up again to avoid a mess. Impurities in gas, and electronic noise in the start of the fill, were also common for ID.

Time Projection Chamber : TPC

The TPC represents the biggest tracking detector of DELPHI and it had a lot of electronics and a number of problems. First of all the pressure inside the TPC volume depends on the outside (cavern) pressure. Three standard pressure plateaus were adopted for the data-taking time. The change of plateau should take part between physics fills but it might not be the best choice if the weather (and pressure) changed fast.

The purity and composition of the gas mixture were big concerns for the TPC team and even some pumps got broken during the last years of service.

The electronics in the TPC barracks was affected by rather frequent FIP crashes. This stopped all data in transmition between the central acquisition and the TPC memory buffers.

All other TPC problems were small compared to the breaking of one wire in sector 6 of TPC. It happened during the night of April 16th 2000 and in spite of endless and hard effort of the TPC crew (like variation of voltage on this and neighbouring wires, gas composition tests, slower ramp up and etc) the sector was tripping nearly all the time and data quality was bad. In June the sector was considered to be lost and in August one row in sector 5 was lost as well. The idea of opening the DELPHI barrel and to do a partial repair of TPC was proposed to the LEP coordination but it wasn't supported since the other three experiments (ALEPH, OPAL, L3) could not afford a two weeks stop of LEP for TPC repair.

Outer Detector : OD

The Outer Detector situated quite far from the IP and a beam pipe but surprisingly had a few of background connected problems too. Around 5-8 blocks from a total of 32 were out of track reconstruction during last year of running making it very tricky in these dead zones. Some of the blocks tended to revive, after being switching off for a while, but high voltage (4.4 kV) and difficulties with separate block operation made the task of putting the block back in service was quite difficult and time consuming for OD shifter.

Forward Chambers : Forward Chamber A (FCA) and Forward Chamber B (FCB)

Both type of Forward chambers experienced minor background spikes problems. Gas purification and quality of data were sometimes a worry as well.

Muon Chambers : Barrel (MUB), Forward (MUF) and Surrounding (MUS)

The MUB was a very unfortunate detector in the matter of electronics. Some CAMAC and FastBus crates tended to have very strange problems which could not be solved by shifters. Technician was called several times from Britain but each time he found nothing wrong since the problems disappeared exactly before his arrival.

The Quality Control central monitor partition suffered from MUB histogram bugs and a separate program based on PAW was used to check the MUB data.

MUF lost 1/8 of his surface in the middle of the summer 2000 due to the dust in the switch-box on top of the chamber.

MUS suffered only from old electronics instability and some minor noise in connection with the background spikes.

2.4.2 2nd group - Calorimetry

High density Projection Chamber : HPC

The HPC was a very big sub-detector needing a lot of electronics situated in the usual crates and racks. The situation with cooling critical - thermometers were installed on these racks and Slow Control shifter checked it twice per shift. The temperature was never below 32 degrees and sometimes close to 36 which led to massive failures and instability in form of noise, high trigger rates etc.

Slow Control software bugs were a usual source of misunderstanding between Slow Control and the HPC teams and the solutions were nearly always temporary and as unstable as the problems.

Forward Electromagnetic Calorimeter: FEMC

The FEMC got sometimes noise in triggers which was usually successfully masked in a matter of days. Background and synchronisation problems were rather common too.

Hadron Calorimeter : HCAL

This most massive sub-detector of DELPHI experienced a typical problem of water vapour in active gas which was always connected with high humidity in the cavern. The jamming signals from dead lamps and other noise sources were a real danger for HCAL too. The Slow Control ramping up (and ramping down) procedure was very long and untraceable which made some Slow Control shifters very concerned in the start (end) of the physics fill and during HCAL voltage trips.

2.4.3 3rd group - Scintillator counters

Time Of Flight : TOF

Problems with trigger, timing and synchronisation were usually solved quickly but the quality of the data was not so fast to improve after each change of parameters and/or electronics.

HOrizontal Flight tagger : HOF

Data acquisition problems, Pandora pickups and jamming from other detectors were usual.

HERmeticity taggers : HER

The weak signals got some noise and background problems. The shifters were sometimes less familiar with its old hardware.

2.4.4 4th group - Particle identification

Ring Imaging CHerenkovs : RICHes

The most vulnerable part of the RICH detectors were the temperature limitations. The states of liquids and gases were watched very carefully by Slow Control but still some problems with data quality were spotted and bad electronics channels needed attention quite commonly.

2.4.5 5th group - Luminosity measurement

Small angle TIle Calorimeter : STIC

The STIC shared a G64 Slow Control processor with VSAT that made both detectors dependent on each other. STIC had both low and high voltage supplies and the high voltage was off during adjustment of the beams making the luminosity and background monitoring impossible before physics.

STIC got the usual problems with electronics components instability by the end of 10 years of work. A few photo-multipliers were lost each year (6 during the last year) before the STIC team received an opportunity to change them.

Very Small Angle Tagger : VSAT

The VSAT typically used to lost a couple of strips after each shutdown due to connector problems and those strips could be revived. This was not a great problem, since the last DELANA versions were always equipped with alghoritms to solve this problem in calculating of the X position.

Signals from one FAD plane (3 or 5) and from one of the strip planes from module 2 tended to disappear due to the bad connectors on the back-plane of the crate. There were no other way to solve the problem except to shaking and moving the boards in this crate. Once the whole of module 4 was lost in the same manner, for one fill.

In the beginning of the year 2000 data-taking period the VSAT trigger ceased to work in the end of first physics fill. It was discovered only two weeks later that the electronics was fine but the cable with T1 signals was accidentally unplugged from central trigger switch-box by the DELPHI trigger team during their work with STIC trigger wires.

A very strange software problem occurred several times during the last three years with no clear reason. The histograms of the VSAT partition in Data Quality Control central monitor sometimes used to have holes and crushed the central monitor. It was like somebody was using the histograms with the same numbers as for VSAT and incoming data went in both directions. All checks for bugs and logical errors in both local and central code, modifications and test runs gave nothing and after a while a problem always disappeared by itself.

2.5 VSAT Hardware

The signals from the VSAT silicon detectors were read out using a track-and-hold method where the peak value was recorded by ADC. The sample time of the signals were around 500 to 650 nanoseconds at laboratory conditions. All of 124 ADC channels per module (12 from FADs, 64 from two X planes and 48 from one Y strip plane) have 16 binary digits.

The track-and-hold circuites were located in the tunnel while the rest of the logics was located in the counting barrack D2 50 meters away. Problems are more or less common to all problems of DELPHI sub-detectors: jamming from electrical and radio-wave sources, heating, unstable cooling, mechanical instability in connectors from partial dismounting of the VSAT and from the fact that we need to switch off a lot of systems during each year a shutdown period.

Still the VSAT electronics survived till the end (10 years) with only 4-6 strips and 1 FAD plane dead by the end of data-taking in 2000. This is quite a decent results taking into account that others 448 strips and 44 FAD planes survived well and needed only a precise re-calibration once or twice per year.

All voltages, bias currents and temperature in modules were monitored constantly during data-taking and test periods by the slow control system of VSAT, connected to the DELPHI Slow Control database [9]. This was a very important feature which gave a lot of useful warnings when the background conditions were dangerous. The synchrotron radiation and off-momentum electron background proved to be very hard to reduce in spite of big efforts which were made by DELPHI and LEP teams [10] for the protection of DELPHI sub-detectors. During September 15, 1995, one essential part of that protection, the closest to DELPHI collimators, were not closed on one side of DELPHI due to operator error. This incident [9] lead to the severe radiation exposure on VSAT inner and outer backward modules. The damage itself produced an increase of bias currents by a factor two-four and the energy resolutions of these modules were decreased somewhere and did not recover to the initial level until the last days of DELPHI. However we could live with that damage.

The energy resolution at 45 GeV was 5 %, at 95 GeV it was around 4 % (it follows the simple parameterisation formula R=35%/E1/2 there E units is GeV). VSAT energy resolution is very stable (Fig. 2.2) for the inner modules and show a small rise (about 1% between start and end of year) in the outer modules due to the higher background from off-momentum electrons there.

The resolution of the silicon strips (1 mm pitch) over the of X and Y coordinates is about 170 microns.

The expected systematic error in relative Luminosity Measurement at LEP I was 0.1% and for LEP II was 1 % in off-line, end-of-the-year processing using STIC data for comparison.

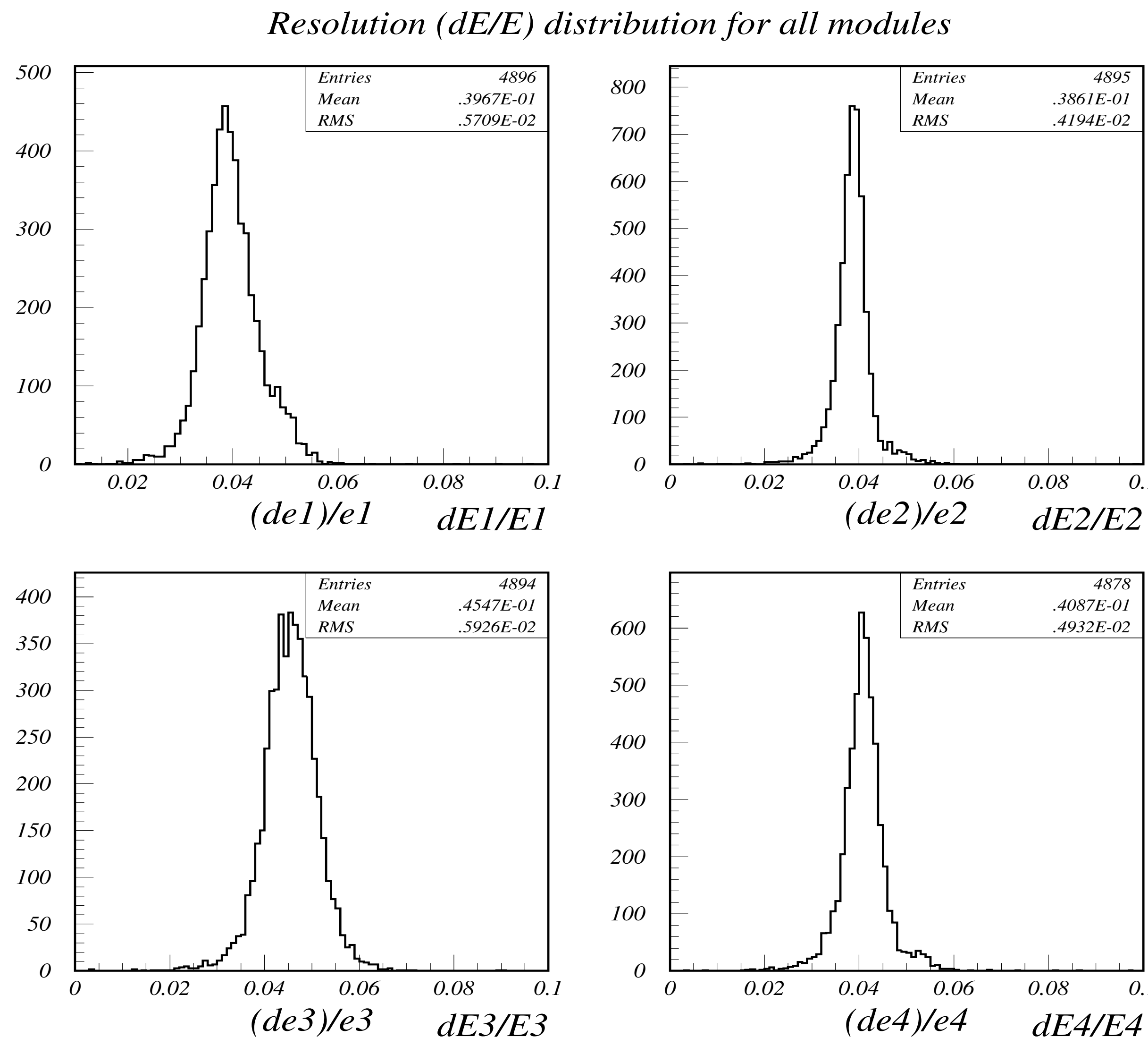

Figure 2.2: VSAT resolution for 95 GeV beam energy (1998).

VSAT electronics can record three kinds of events:

Bhabha (BH) - defined as coincidence between hits into diagonal modules with signals above threshold.

Single electron (SE) - defined as energy deposition above the low energy threshold in any of four modules. Can be immediately down-scaled with different factors for outer and inner modules (different SE background conditions).

False Bhabha (FB) or Accidental Bhabha - defined as coincidence between one module and it's diagonal module but delayed by four LEP bunch crossings. The whole triggering took too much time - 4 periods of 22 microseconds each after Beam Cross Over signal arrival (BCO). That's why this kind of trigger was switched of prior to LEP II phase (False Bhabhas were selected in off-line mode). Energy thresholds is high as for Bhabha trigger.

The VSAT hardware composition and overall picture of data flow in represented on the next page.

The triggering and data acquisition system of the VSAT was quite untypical for DELPHI due to the high rate of events and positions of modules. It is mainly independent of main data acquisition system of DELPHI, i.e. we hold our own buffer to avoid triggering the overall DELPHI data acquisition. This feature was a frequent source of miss-understanding and mistakes when DELPHI make trigger changes and upgrades.

Basically, VSAT T1 level triggers don't affect DELPHI. They just get stored in the VSAT data storage buffer. Initially it was designed to store up to 20 events. But since the rate was high the efforts was done to compact data in this buffer which gave a bigger capacity. The maximum capacity of this VSAT T1 events bank was 28 events by 2000. When the buffer becomes full VSAT makes a T2 event and giving a trigger for the whole DELPHI (transferring the events in buffer to DELPHI). But as one can see from distribution below (Fig. 2.3) it did not very often - usually some other sub-detector triggers DELPHI (and VSAT) before our buffer is full. The VSAT buffer is moved to the central DELPHI partition and is written on the tape. The buffer length was 12-20 events long in the beginning of DELPHI and 25-28 events long during last two years.

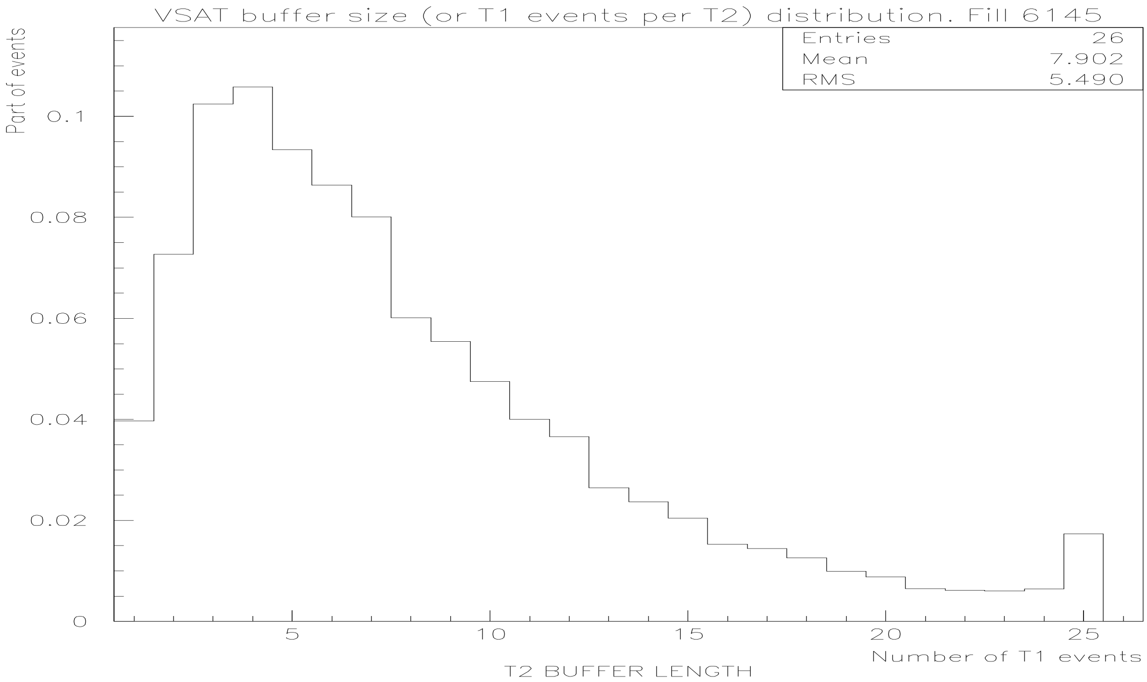

Figure 2.3: VSAT buffer size (number of T1 events per one T2 event) distribution during usual physics fill 6145 (19.08.1999) with 99.828 GeV beam energy. Picture made by PAW using file created by VSAT on-line local monitor.

2.6 Processing of Data

VSAT data was written on the same cassettes as all of the DELPHI data stream. Data was transferred by local network to the CERN computer centre instantly during data-taking. The raw data was processed and stored temporary there. But in order to reprocess the VSAT part of the data we needed a separate set of files with VSAT information about each event. All these files should be available for the VSAT team anytime, i.e. be stored on our own disks and cassettes.

Such files were provided by the DELANA program which used to run in the CERN-DELPHI computer centre all the time during the data-taking periods and afterwards. DELANA checks the raw data files, selects the real physical events, decodes them, calculates the energy response and draws tracks from each detector. In other words it gives a clear picture of the event as it was seen by DELPHI.

In DELANA's there is a part called LUMANA (i.e. connected with luminosity) which extracts, checks and writes special .VST files in a common DELPHI directory. From this directory files are transferred to the VAX station which belongs to the VSAT team. Here the real reprocessing starts more or less automatically as DELANA (LUMANA) provides the files. The monitoring program THOR created by Andreas Nygren [4] looks for new arriving VST files and if they are available in requested size (enough to process one fill of physics) then the ODEN program starts. ODEN was made by Per Jonsson [5] and has a task making summary ntuple files with basic parameters of one fill of LEP (energy, beams intensity, background, luminosities) and the corresponding DELPHI runs (time, detectors status and etc with a stress on specific VSAT information). ODEN also proceeds with one important task mainly based on a COMPACT command file which was coded by Eric Vallazza at 1992. The task of COMPACT is to archive, compact and combine several big VST files into one FX file per fill. Then it can be stored on local disks, cassettes (using the Exabyte connected to the same VAX station) and common HPSS (High Performance Storage System) of long duration, i.e. a high capacity storage system based on disks and cassette drivers driven by robots.

Afterwards the FX files can be used several times with summary ntuples. Both FX and summary ntuples are necessary for the next reprocessing phase which is performed by VSDIAG - Fortran 77 program. The program was originally written by many people [6] but need to be modified to a very high degree each year or even with each new DELANA version. The DELPHI software team produces 4-8 versions of DELANA per year of data-taking and only the last one is running over the whole set of raw data (by the end of year or after the end of data-taking period).

Only after VSDIAG has finished one fill one can receive information about Single electrons (for background checks), Bhabha events (for beam parameters and luminosity estimation) and gamma-gamma events (two photons physics analysis) in that fill. The information comes in a form of histogram and ntuple files (two per fill) and gamma-gamma text files with event numbers.

The overall view on the off-line (short term results are obtained after two-six weeks after data-taking) reprocessing can be seen on the next page.

Chapter 3

Conclusions

DELPHIs last data-taking period (as well as other three experiments: ALEPH, OPAL, L3) was stopped at November 2nd, 2000. VSAT was dismounted soon afterwards. The modules proved to be only very little radioactive (less then concrete walls of DELPHI cavern actually). Two modules with a part of the beampipe will be transferred to Lund to be exposed in the museum of Physicum equipment. The last year data processing from VSAT (especially gamma-gamma physics events) is not finished yet. Data from the last LEP II phase (1998-2000) will be reprocessed again and are supposed to be used in some analysis for few years.

The VSAT raw data took a huge amount of disk space (more than 30 Gb) over the last three years (LEP II phase). The detector itself proved to be robust and survived years of harsh radiation environment and millions of leptons (as it shown in the Appendix 4).

Using VSAT off-line data became more complicated at LEP II since the background rose dramatically (especially during June of 2000). The VSAT suffered from some radiation damage, electronic noise, weak energy resolution, bias currents increase and the software need to deal with background spikes, corrupted events, difficulties with selecting good events from background. Still it was possible to calculate the luminosity with precision to 1%, the beam parameters could be defined. A comparison of these parameters with data from Vertex Detector of DELPHI was made and a lot of gamma-gamma and Bhabha events were selected from tape.

The on-line values provided by VSAT: luminosity and single electron background (Bckg 2) were provided as well as before at LEP I within 5-10 % agreement with STIC and LEP beam monitor detectors.

During summer of 1999 simulation was made by using programs FASTSIM [7] (based on DELPHI Monte-Carlo simulation standard) and GEANT [13] (general purpose Monte-Carlo simulation package). The aim of this study was the estimation of energy reconstruction problems which VSAT could face with leptons energy above 100 GeV. The results showed that the electromagnetic shower stays within the calorimeter and the leakage is still negligible in spite of the fact that VSAT was designed for the energies well below 95 GeV. The last year of data-taking confirmed this simulation based estimation.

The geometry of VSAT was changed prior to LEP II phase. The increased acceptance give a bigger Bhabha and off-momentum electrons flux as well as a large number of electrons from gamma-gamma events in DELPHI. This change gave a two fold rise of gamma-gamma statistics and in the same time increased the VSAT trigger rate because of flux of the False Bhabhas triggers came often then before. The False Bhabhas were sorted out later during off-line reprocessing. The quality of selection and check of Bhabha events (separation from background Single Electrons) remained the same as before and the final gamma-gamma events sample wasn't affected by that background too much since most of it located in the beam plane.

The trigger rate was also decreased by a pure logical method, increasing the T1 events buffer length, which gave a VSAT T2 trigger rate low enough to keep DELPHI trigger system working with acceptable dead-time. The number of corrupted events was around 0.2 % during all years of data-taking except for the last two months then it was around 1 % due to more unstable conditions of the beams and background.

The VSAT data reprocessing and storage had only a problem of format due to the change of T1 buffer size and temporary disk space shortage problems when DELANA version changes occurred, Y2K bug and with new run numbers (8 digits instead of 7), a standard adjustment common for the DELPHI collaboration.

Chapter 4

Acknowledgments

My work with the VSAT detector was first of all a good opportunity of learning real physics. Besides it helped me to understand the importance of many aspects of experimental physics as well, e.g. a lot of useful experiences connected with computers and information technology, visualisation of data and logistic plus the importance of robust hardware and good software support. The training concerned the ability and rules of working in an international team. Smart approach to my own schedule of work and free time. The work itself gave me confidence in my knowledge and ability to learn more skills with some of them very useful.

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Appendix 1

Appendix 2

Appendix 3

Appendix 4