SLAC-PUB-7203
TOHOKU-HEP-96-01
June 1996

The SLD VXD3 Detector and Its Initial Performance*

F. Suekane
Tohoku University
Sendai 980-77, Japan

Representing the SLD/VXD3 Group **
Stanford Linear Accelerator-Center, Stanford University, Stanford, CA 94309

Abstract

The SLD collaboration completed construction of a new CCD vertex detector (VXD3) in January 1996 and started data taking in April 1996 with the new system. VXD3 is an upgrade of the original CCD vertex detector, VXD2, which had successfully operated in SLD for three years. VXD3 consists of 96 large area CCDs, each having 3.2 million $20\mu m \times 20\mu m$ pixels. By reducing the detector material and lengthening the lever arm, VXD3 is expected to improve secondary vertex resolution by about a factor of two compared with VXD2. The new three-layered structure enables stand-alone tracking without any ambiguity and its extended size along the beam direction improves the polar-angle coverage to $|\cos\theta|<0.85$. An overview of this detector system and its initial performance are described.

Presented at the 5th International workshop on Vertex Detectors (Vertex '96)
Chia, Italy, June 16-21, 1996.

* This work was supported by Department of Energy contracts: DE-FG02-91ER40676 (BU), DE-FG03-93ER40788 (CSU), DE-FG02-92ER40715(Massachusetts), DE-AC02-76ER03069 (MIT), DE-FG06-85ER40224 (Oregon), DE-AC03-76SF00515 (SLAC), DE-AC02-76ER00881 (Wisconsin), DE-FG02-92ER40704 (Yale); National Science Foundation grant PHY-92-03212 (Washington); the UK Particle Physics and Astronomy Research Council(Brunel and RAL); the Istituto Nazionale di Fisica Nucleare of Italy (Bologna, Ferrara, Frascati, Pisa, Padova, Perugia); and the Japan-US Cooperative Research Project on High Energy Physics (Nagoya, Tohoku).
** SLD/VXD3 Group members and institutions are listed after the references.

1. Introduction

The SLD (SLC Large Detector) [1] experiment studies the nature of elementary particles using highly polarized weak neutral bosons, Z^0s, which are produced by the SLC (SLAC Linear Collider). At SLD one of the most important analysis topics is heavy quark physics. Generally heavy quarks from Z^0 decays decay a few millimeters from their production point and weak asymmetry properties become maximum at the smallest polar angles with respect to the beam line, so precise vertex resolution down to small polar angles is essential to perform high quality heavy quark physics. A very small beam size ($2.4\mu m(x)\times 0.8\mu m(y)\times 700\mu m(z)$), in conjunction with a small beampipe radius (r=2.3cm) at SLC make SLD an ideal place to exploit a precise vertex detector. The long inter-collision time (8.3ms) of SLC enables the use of CCDs (Charge Coupled Device). SLD's previous CCD vertex detector; VXD2 [2], operated successfully for three years and has produced a number of important physics results [3]. However, it was realized that if we constructed a new vertex detector making use of current technology and our VXD2 experience, the quality of the heavy quark physics would substantially improve, in particular the measurement reach for the Bs mixing parameter would extend to $x_s=15$ [4]. Under these circumstances, the SLD group was given approval to construct the new vertex . detector, VXD3 [5] in March 1994 and finished its construction in January 1996. From April 1996, SLD started data taking with this new system. In the next section the VXD3 system is briefly described and its initial performance is discussed in section 3.

2. The VXD3 Detector

- **The CCD[6]**

Fig.- 1 shows a schematic of the VXD3 geometry and Fig.-2 shows the CCD layout. 96 of these large area CCDs are used in the detector. The CCD is an n-buried channel device fabricated on a p-type epitaxial layer ($\sim 20\Omega cm$) and having a p+ substrate ($<0.02\Omega cm$). The epitaxial layer is about $20\mu m$ thick. The pixel size is $20\mu m\times 20\mu m$, so that the volume of an active unit is $(20\mu m)^3$. As a typical minimum ionizing particle (MIP) hit is contained within a few pixels, the intrinsic position resolution (σ) is expected to be at the few micron level. The active area of the CCD is $80mm\times$ 16mm without any dead regions. The total number of pixels per CCD is $4{,}000\times 800$, which are read out through 4 output nodes at the comers of the device. The readout register is based on two-phase clocking ("R-clock"). The image area is based on three-phase clocking ("I-clock"). The R-clock speed is 5MHz while the I-clock speed is 100KHz. The detector is operated at a temperature of -50^oC to reduce thermal noise and the effects of radiation damage. The typical output responsivity is $2.8\mu V/e$. The readout noise (σ) is about 60 electrons while a typical MIP deposits 1,200 electrons in a CCD. The typical threshold is set about 300 electrons, which gives a detection efficiency for MIP of 98% or better. The radiation hardness of the CCD was studied using a radioactive ^{60}Co source. Although approximately a 10% gain degradation was observed after a dose of 15kRad, no serious degradation was observed at the expected SLD dose level of a few kRad.

- **Mechanical Structure**

The physical dimension of a CCD is approximately $82.4mm\times 16.6mm\times 0.15mm$. Two CCDs are assembled onto a polyimide/beryllium sandwich to form a ladder; one CCD is mounted on the inner side of the ladder extending south of the center and one on the outer side of the ladder extending north. The beryllium stiffener is $216.7mm\times 0.38mm$ and the CCDs have approximately one millimeter of overlap, forming an active area of $159mm\times 16mm$. The copper traces on the polyimide film carries signals from the inner end of the CCDs to the end of the ladders. The thickness of each ladder is 0.4% radiation length. The ladders are supported at each end by beryllium rings mounted to the inner faces of the detector endplates. The support structure is made from instrument grade beryllium, which is match pinned and doweled to achieve a stable environment. 48 ladders are arranged in three coaxial cylindrical layers, located at nominal radii of 28.0, 38.1 and 48.3 mm around the beam pipe. The inner, middle and outer layers contain 12, 16 and 20 ladders, respectively. The polar angle coverage extends to $|\cos\theta|<0.85$ if three hits are required and, $|\cos\theta|<0.90$ if at least two hits are required. The beampipe is made of a beryllium cylinder of 0.76mm thickness and 23.2mm inner radius. There is a $50\mu m$ thick titanium liner inside the beampipe to absorb background soft photons. A 0.5mm thick beryllium jacket surrounds the beampipe. Every ladder was optically surveyed individually before assembly, and each barrel was surveyed following assembly. The CCD system is surrounded by a low mass foam cryostat and cooled by boil-off nitrogen gas down to the operating temperature. The total power dissipation in the cryostat is about 20W. The expected impact parameter (IP) resolution attainable with this structure is,

$$\sigma_{xy}(\mu m) = 9 \oplus \frac{29}{p\sin^{3/2}\theta}, \quad \sigma_{rz}(\mu m) = 14 \oplus \frac{29}{p\sin^{3/2}\theta}$$

where p is the track momentum measured in *GeV/c.* This is the best IP resolution among the existing colliding beam detectors.

- **Readout Electronics**

As shown in Fig.-3, the analog data from 6 CCDs (24 channels) are fed into an A/D board, which is mounted on the beampipe, and then to a FASTBUS Data Acquisition (DA) board through optical cables after digitization. The A/D board supplies the necessary clock signals and bias voltages to the CCDs. The CCDs are operated in a full frame readout mode with continuous charge accumulation on the output node capacitor, resetting at the end of each row. The beams collide every 8.3ms. The readout electronics wait for about 5ms after each beam crossing to see if there is an event trigger. If there is no event trigger, the A/D board sends 250 contiguous I-clocks followed by 412 R-clocks (image area + dummy pixels) in order to sweep out the background charge (Fast Clear Mode). It takes eight beam crossings to sweep out the entire image area. If an event trigger is issued, the A/D board is switched to Read Out Mode, i.e. each I-clock is followed by 412 R-clocks. Eighty one rows are read out per beam crossing and it takes 0.2 seconds to read out the entire detector. The CCD signal is at first amplified by a two-stage amplifier of total gain 100 and then digitized by an 8 bit flash ADC. The resulting data, which are 8bits$\times$ 24 channels $\times$ 5MHz, are parallel/serial-converted up to 1 bit$\times$ 960MHz by a series of XILINX[7] field programmable gate arrays and Hewlett-Packard[8] Gigabit Rate Transmit -Receive chipsets. Finally, a 1.2GHz FINISAR[9] optical transmitter converts the electronic signal to an optical signal and sends it to the DA board via a fiber-optic cable. On the DA board, the data are converted down to 48 bits$\times$ 20MHz then all the pixel amplitudes are stored in 24 VRAMs (250KB each). In parallel with this, the same data are fed to 6 cluster processors. The cluster processor looks for “real hits” based on a digital noise falter and an optimized cluster-finding method and then outputs an accept signal in real time [10]. Typically the data size reduction factor by the cluster processor is more than 10^4 while retaining a good MIP efficiency. The accept information is stored in Accept RAM (SRAM). A CPU (MC68LC040[11] @33MHz) reads the contents of the Accept RAM then transfers only the data of necessary pixels from the VRAMs to its main memory. Later, the SLD data acquisition system comes to read this main memory and sends the data to magnetic tapes together with the data from other detector components.

3. Initial Performance

The data-taking with VXD3 started in April 1996 and we have taken 25,000 Zs by the time of this conference. In normal beam conditions, the average data size is 50 to 60KB, corresponding to a few thousand charge clusters, which mostly come from background tracks and X-rays. The average background density is thus a few hits per cm^2, which is quite a manageable level, taking the detector granularity into account. Software work is going on to study and improve the detector's tracking performance. So far, a detailed alignment has not been attempted. However, some preliminary and promising initial performance results have been obtained after two month of running. Fig.-4 shows an example of a (presumably) *b* -quark event reconstructed by using the central drift chamber and VXD3. (Note that the sizes of the hits in this figure represent the cluster amplitudes. The actual hit sizes are too small to be seen in this scale.) If a magnified view is looked at, two vertices are clearly seen a few millimeters off the initial vertex in both the xy and rz views. It has been proven by VXD2 that the three dimensional vertexing capability can be used very effectively to obtain a pure *b* -quark event sample with high efficiency[3]. Fig.-5 shows the residual of the 2nd-layer hit position with respect to the straight track determined by 1st- and 3rd-layer hits. B y fitting to the Gaussian distribution, the initial overall position resolutions, $\sigma_{r\phi}=17\mu m$ and $\sigma_z=14\mu m$, have been obtained. The intrinsic resolutions of $\sigma_{r\phi}=4\mu m$ and $\sigma_z=5\mu m$ have been obtained from the residual distributions of a combination of 3 particular CCDs of different layers as shown in the fig.-6. Currently the overall position resolution is dominated by alignment errors and we expect it to approach the level of the intrinsic position resolution after a detailed track based alignment as was demonstrated in the past with VXD2. Fig.-7 shows the momentum dependence of the link efficiencies for the cases of a) at least 2 layers out of 3 layers, b) all 3 layers, having associated CCD hits to good CDC tracks. They show that the 2 point link efficiency is 98%, and that of 3 points, 93%. The inefficiencies, again, come mostly from the alignment error, and after the fine alignment those numbers are expected to significantly improve. One thing to be noted is that these results were obtained within a month or two after the first data were taken (actually, within a few weeks after the last major hardware debug). This fact shows another strength of VXD3, that is the 3 dimensional structure of a fine pixel device enables an unambiguous tracking and easy, yet reliable analysis.

Finally, we have encountered the following unexpected troubles since the installation of the detector, although none of them is serious.

- Dead Channel: One channel (0.25% of the total area) does not respond. A broken bonding wire is suspected. This is not fixable if that is the case.
- Hit Smearing: For two channels (on same CCD), the charge leaks in neighbor pixels in the read out register. As a result, the pulse height per pixel becomes low and the detection efficiency is sacrificed (~50%). This is because this particular CCD chip requires higher R-clock voltage than others. This will be freed in the next run period by raising the voltage.
- Electronics Cooling: The contact of the A/D board to the heat sink turned out to be not good enough in the final full assembly and some A/D boards become hot. This will be freed using better thermal contact method in the next run period.
- Beam Related Noise: Initially the links between some A/D boards and DA boards were occasionally lost due to a spurious command caused by a beam related glitch. This has been cured by putting the electronics system into the inactive state during beam crossing.

4. Summary

After two years of design and construction, the VXD3 detector has started its operation successfully. Intensive work is still going on to optimize the detector alignment and improve the performance. Currently, overall and intrinsic position resolutions of 17μm and 5μm, respectively, have been achieved in both xy and z direction. A two-hit link efficiency of 98%, and a three-hit link efficiency of 93% have already been obtained. Significant improvements from these values are expected after the detailed alignment work which is now underway.

References

[1] SLD Design Report, SLAC-273 , UC-43D (1984), and revisions.

[2] M. G. Strauss representing the SLD collaboration, SLAC-PUB-6686, Ott 1994 and, SLAC-PUB-5970, Oct. 1992.
C.J.S. Damerell representing the SLD collaboration, SLAC-PUB-5906, Aug 1992.
C.J.S. Damerell et al., Nucl. Instr. Meth. A 288 (1990) 236-239, Dec 1990.

[3] For example, K.Abe et al, Phys. Rev. Lett. 75:3609, 1995, Phys. Rev. Lett. 75:3624, 1995, Phys. Rev. D52:4828, 1995, Phys. Rev. D53:1023, 1996.
E. Etzion representing the SLD collaboration, SLAC-PUB-06-7 170, May 1996.
J.A.Jaros representing the SLD collaboration, SLAC-PUB-7067, Dec 1995.

[4] 'Proposal to Upgrade the SLD Vertex Detector', VXD3-NOTE-1, Ott 1993.
'Response to Questions from the EPAC Concerning the Proposal for an SLD Run Extension and a Vertex Detector Upgrade' VXD3-NOTE-4, Feb 1994.

[5] J.E. Brau representing SLD VXD3 Group, SLAC-PUB-95-7070, Dec 1995.
SLD Vertex Detector Upgrade Group, International Europhysics Conference on High Energy Physics (HEP95). Aug. 1995. SLAC-PUB-95-6950

[6] The CCDs were manufactured by EEV Inc., Chelmsford, Essex, England.

[7] XILINX, Inc., San Jose, California, USA.

[8] Hewlett-Packard, Palo Alto, California, USA.

[9] FINISAR Corp., MenloPark, California, USA.

[10] K.Hasuko, VXD3-NOTE-40, Mar 1996.

[11] Motorola Corp., Enblewood Cliffs, New Jersey, USA.

The SLD/VXD3 Group

K.Abe[h], A. Arodzero[i], C.Baltay[l], J.Brau[i], M. Breidenbach[g], P. N. Burrows[d], A. Chou[g], G. Crawford[g], C. Damerell[f], P. Dervan[a], D. Dong[d], W. Emmet[l], R.English[f], E. Etzion[a], M. Foss[g], R. Frey[i], G. Haller[g], K. Hasuko[h], S. Hertzbach[c], J. Hoeflich[g], J. Huber[i], M. Huffer[g], D.Jackson[f], J. Jaros[g], J. Kelsy[d], H. Kendall[d], I.Lee[d], V. Lia[d], L.Lintern[f], M.Liu[l], S. Manly[l], H.Masuda[g], T. Moore[l], T.Nagamine[h], N. Ohishi[e], L. Osborne[d], D. Ross[d], J.Russell[g], V. Serbo[k], N. Sinev[i], J. Sinnott[l], K. SkarpaasVIII[g], M. Smy[b], J. Snyder[l], M. Strauss[c], Su Dong[g], F. Suekane[h], F.Taylor[d], A.Trandafir[c], T. Usher[g], R. Verdier[d], S. Watts[a], E. Weiss[j], J.Yashima[h], H. Yuta[h], G.Zapalac[k]

[a]*Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom*
[b]*Colorado State University, Fort Collins, Colorado 80523, USA*
[c]*University of Massachusetts, Amherst, Massachusetts 01003, USA*
[d]*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[e]*Nagoya University, Chikusa-ku, Nagoya 464, Japan*
[f]*Rutherford Apple ton Laboratory, Chilton, Didcot, Oxon OX11 0QX, United Kingdom*
[g]*Stanford Linear Accelerator Center, Stanford, CA 94309, USA*
[h]*Tohoku University, Aramaki, Sendai 980-77, Japan*
[i]*University of Oregon, Eugene, Oregon 97403, USA*
[j]*University of Washington, Seattle, Washington 98195, USA*
[k]*University of Wisconsin, Madison, Wisconsin 53706, USA*
[l]*Yale University, New Haven, Connecticut 06511, USA*

VXD-3 GEOMETRY

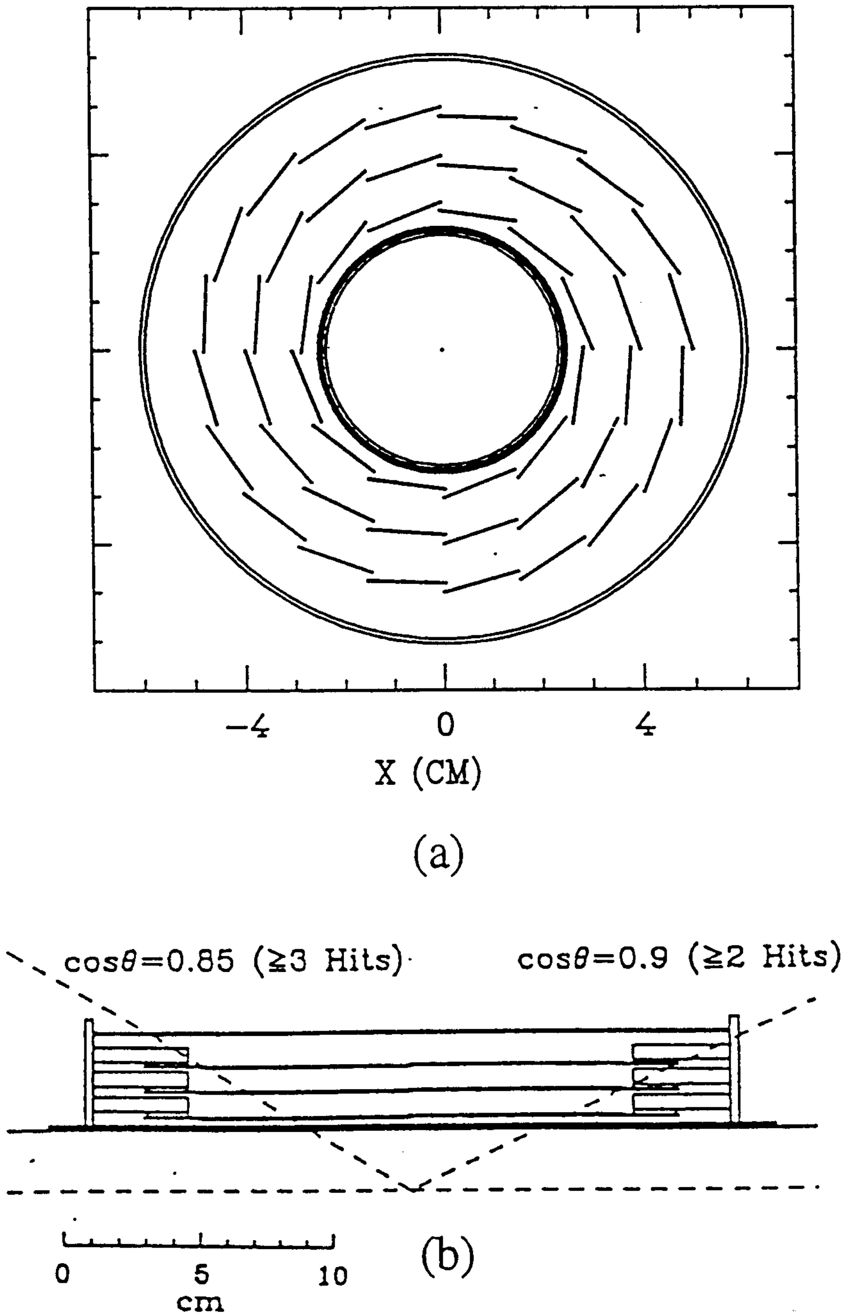


Fig. 1. Schematic view of the VXD3 geometry, (a) for xy view and, (b) for rz view.

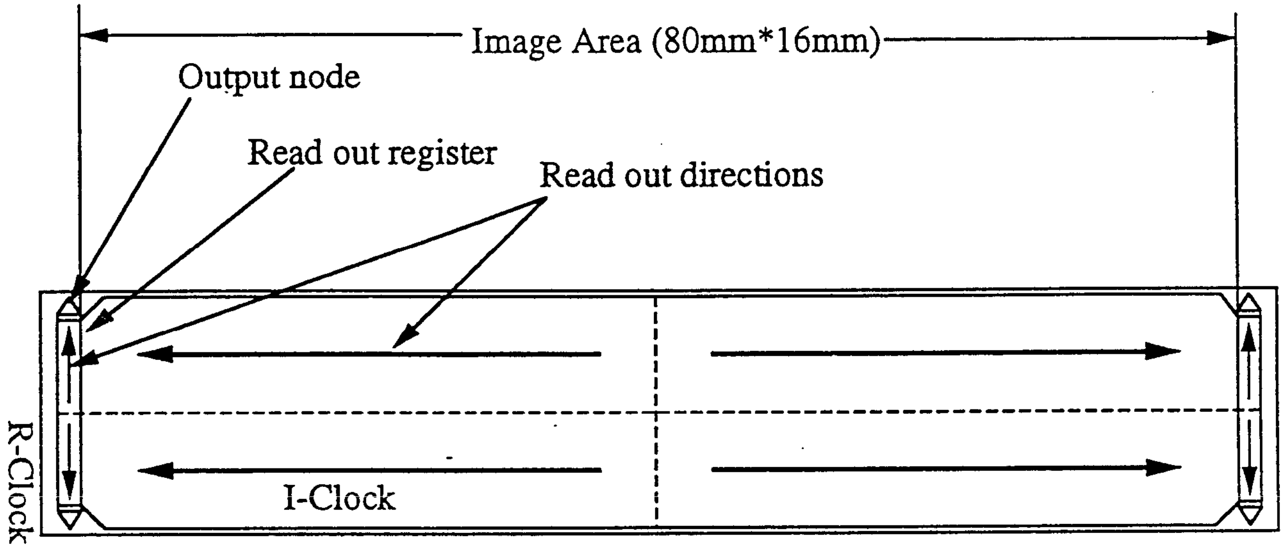


Fig. *2*. The VXD3 CCD. The active area is 80mm*16mm and the pixel size is 20µm*20µm (4000*800 pixels in total.) The epitaxial layer is 20µm thick. The data are read out via 4 output nodes.

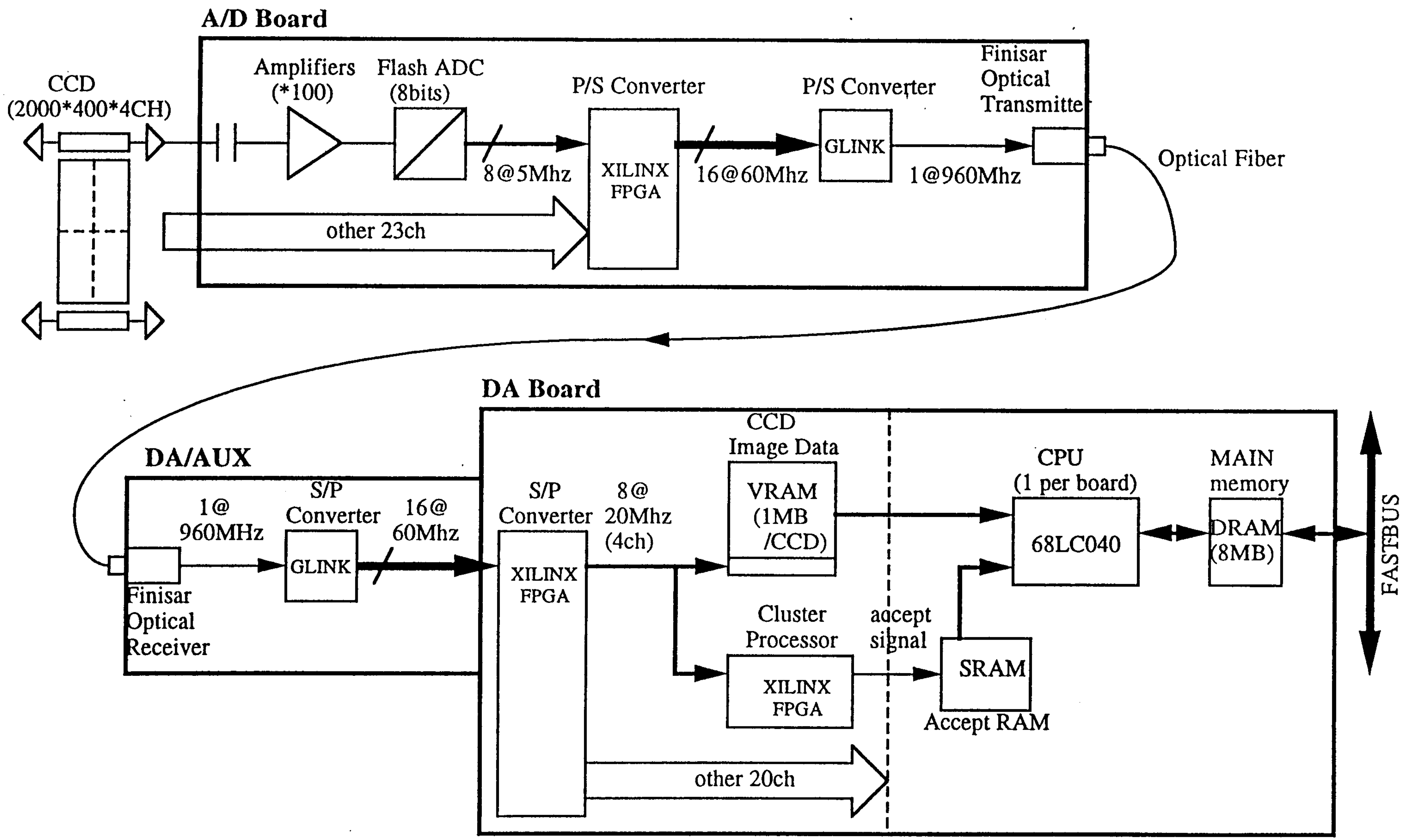
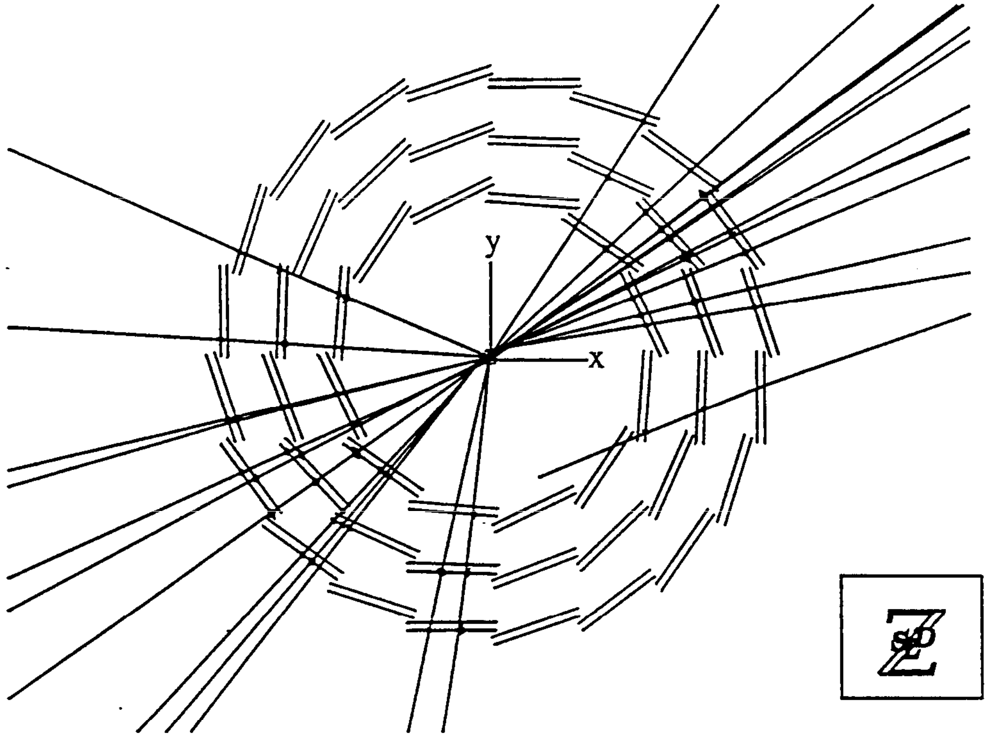
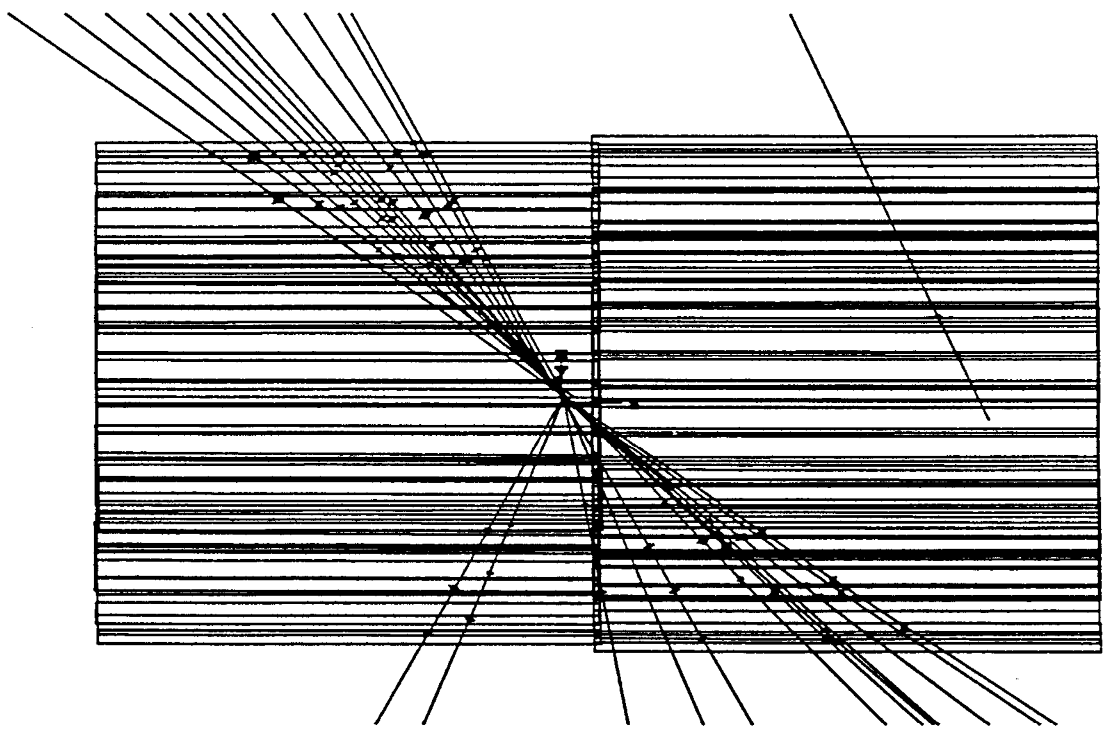


Fig. 3. The VXD3 readout electronics,



(a)



(b)

Fig. 4. Reconstructed track and associated CCD hits, (a) for xy view and, (b) for zx view.

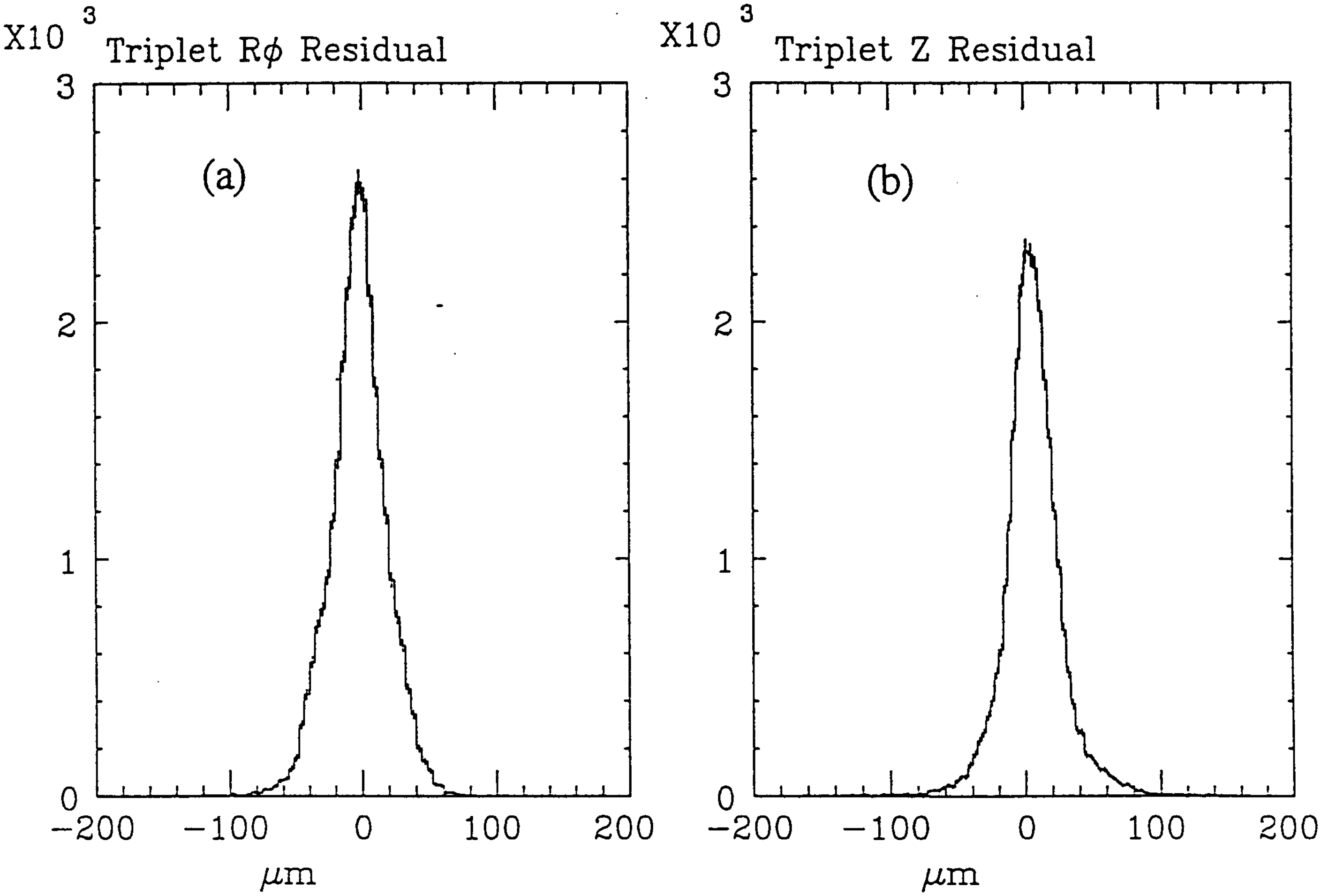


Fig. 5. The distribution of residuals of the 2nd layer hit position from the straight track determined by 1st and 3rd layer hits, (a) in $r\phi$ direction and, (b) in z direction. Corresponding position resolution is currently $17\mu m(r\phi)$ and $14\mu m(z)$, respectively. They are dominated by alignment errors which are expected to be reduced to a few micron level after the final alignment.

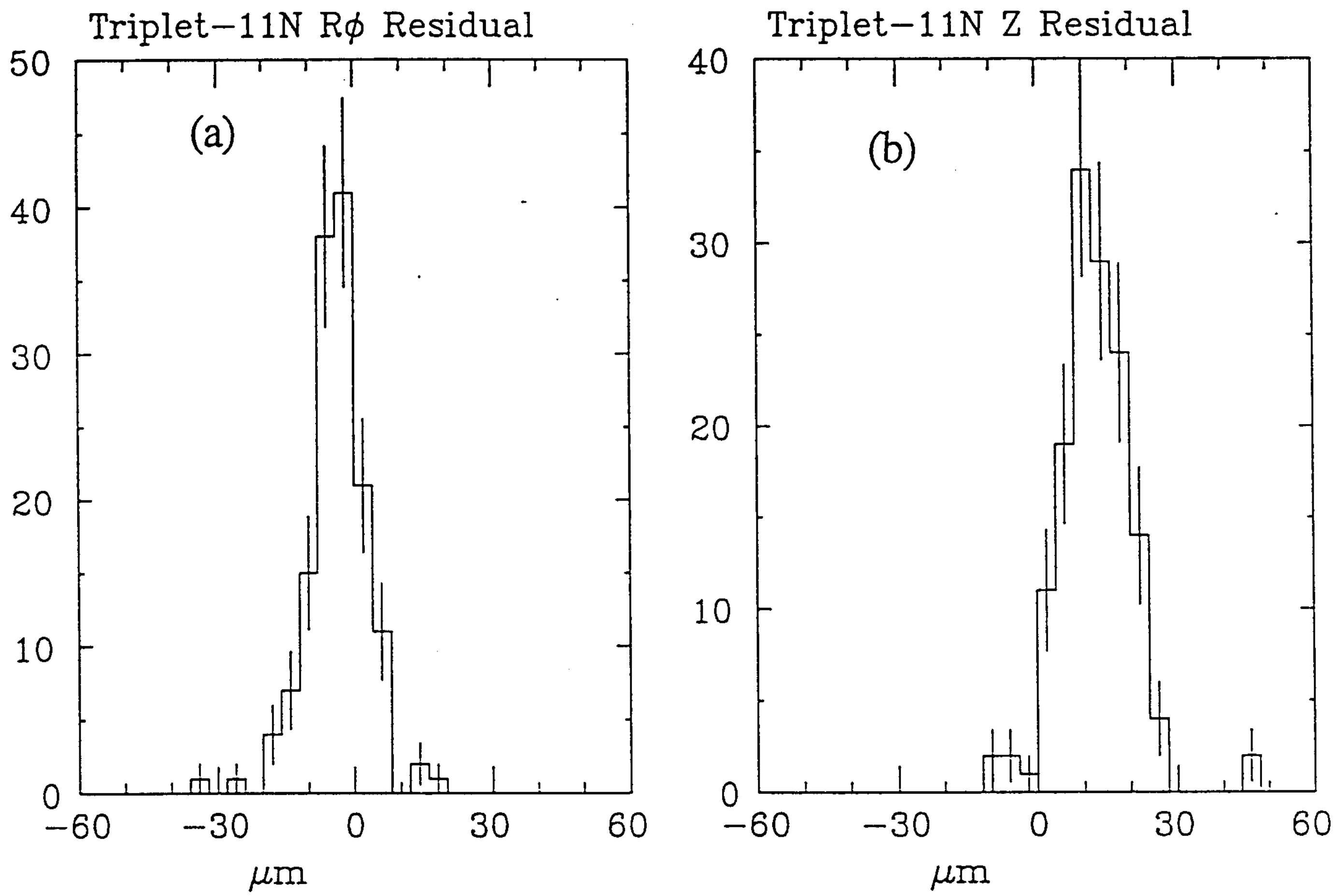


Fig. 6. Same histogram as in fig.-5 but the three hits are taken from particular three CCDs, one at each layer. This is insensitive to the overall alignment error and indicates CCD's intrinsic resolutions, which are 4.2μm($r\phi$) and 5.1μm(z).

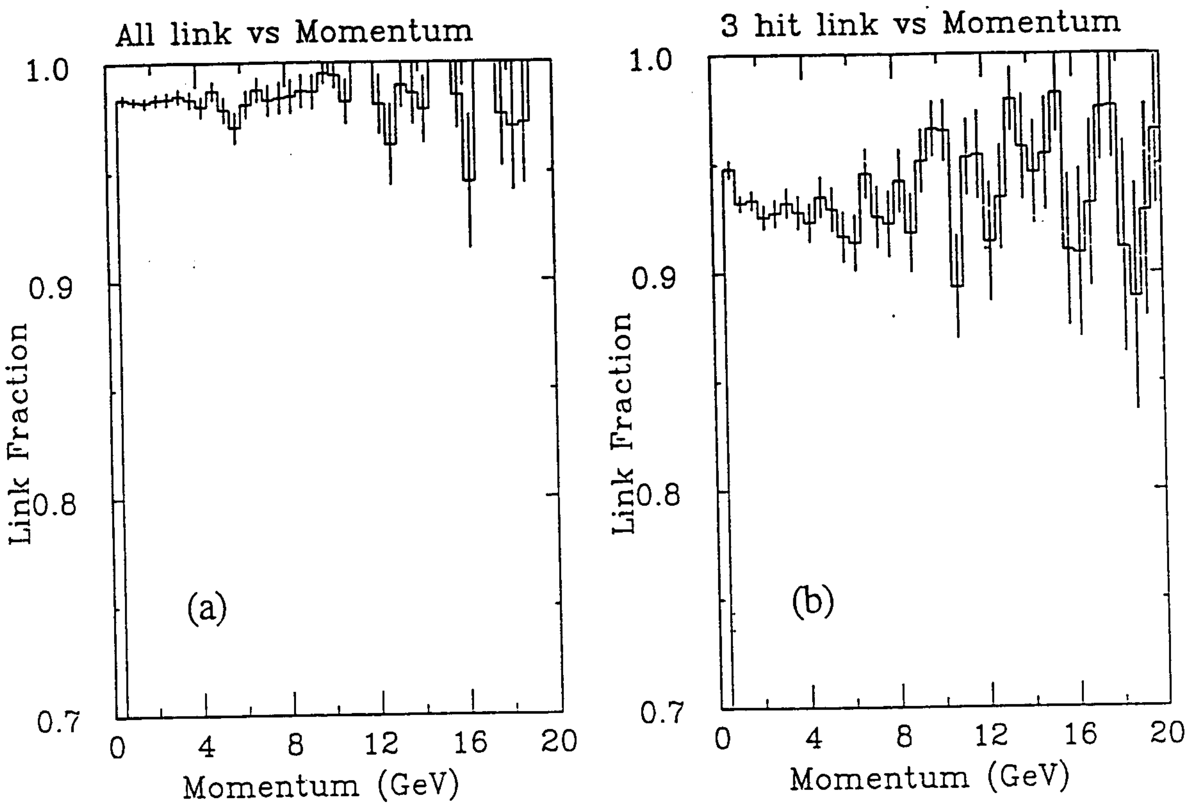


Fig. 7. Momentum dependence of the link efficiency, (a) for the case that at least two layers out of three layers have track associated CCD hits and, (b) for the case that all three layers have hits. The inefficiency is due to alignment error and will improve after the fina1 alignment.