DEPFET,
a monolithic active pixel sensor for the ILC

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1 Introduction

For the accurate measurement of Higgs branching ratios and properties as well as precise studies of physics processes beyond the Standard Model at the International Linear Collider (ILC), efficient distinction of heavy quark flavors, most notably of bottom and charm quarks, is a must. This requires precise secondary and even tertiairy vertex detection, correct assignment of every track to the correct vertex and determinenation of the jet charge.
Since the impact parameters of b-quarks is in the order of $\sim$300 μm and of c-quarks $\sim$100 μm, the challenge for a vertex detector at the ILC is to build a very low mass, high precision vertex detector. The aims are a single hit resolution better than 5 μm and a radiation length of $\lesssim$0.1%X_0, which corresponds to 50 μm thick silicon sensors. The very low mass requirement implicates that no active cooling can be used. Therefore, the detectors power consumption is limited to amounts that can be removed by flowing gas through the detector.
Due to the very high beamstrahlung rate near the interaction point, which produces e^+e^- pairs in vast numbers, the background conditions and the time structure of the accelerator are leading to detector occupancies of $\sim$100 hits/mm^2/bunch train ($\sim$ 1ms) for a pixel detector situated 15 mm away from the beam line.
Also the time structure of the ILC provides a challence. There will be 2820 bunches per pulse, which are spaced 337 ns apart, leading to a pulse train of 950 μs which has a repetition rate of 5 Hz. The aim is to read out the sensors 20 times during a bunch train. This requires a row readout rate of 20 MHz. To limit the power consumption the readout chips need to be switched off in between the bunch trains.
The radiation load is modest. The detector has to withstand 200 krad for 5 years operation.

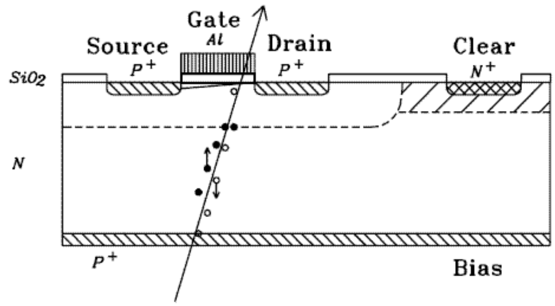

Figure 1: *Principle of operation of a DEPFET pixel structure based on a sidewards depleted detector substrate material with an imbedded planar field effect transistor.*

2 DEPFET pixel structures for the ILC

The DEPleted Field Effect Transistor structure, abbreviated DEPFET, provides detection and amplification properties jointly. The principle of operation is shown in figure 1. A MOS or junction field effect transistor is integrated onto a detector substrate. By means of sidewards depletion, appropriate bulk, source and drain potentials, and an additional deep-n-implantation, a potential minimum for electrons is created right underneath the transistor channel ($\sim$1 μm below the surface). This can be regarded as an internal gate of the transistor. A particle entering the detector creates electron-hole pairs in the fully depleted silicon substrate. While the holes drift to the rear contact of the detector, the electrons are collected in the internal gate where they are kept stored. The signal charge leads to a change in the potential of the internal gate, resulting in a modulation of the channel current of the transistor. The signal charges are cleared out of the internal gate by a positive voltage at the CLEAR contact. Note that the signal is not destructed by the read out until the clear pulse is issued, hence allowing multiple readout. The low noise is obtained because of the small capacitance of the internal gate (several 10 fF) and the absence of external connections to the first amplification stage. The high signal is due to the charge collection in a fully depleted bulk. Both together yield a very large S/N ratio. For particle detection at the ILC the use of very thin ($\sim$ 50 μm) detectors, still operated with large S/N figures and a very low power consumption, are targeted.

3 Current status

Many of the ILC requirements have already been addressed. For instance, the radiation tolerance against ionizing radiation of the DEPFET has already been demonstrated. The required thinning of the device from 450 μm down to 50 μm has been successfully performed on test structures. The estimated power consumption is below 5 Watt, so no active cooling is required.

3.1 Testbeam results

450 μm thick prototype DEPFET modules have been tested in the laboratory and in a 6 GeV electron testbeam. The main results using a DEPFET with 22×36 μm^2 pixels are shown in figure 2. The most probable signal is 1835±4 ADC, the noise 16.40±0.01 ADC, yielding a S/N-ratio 112.0±0.3. The hit positions are reconstructed using the η-algorithm. This yields a residual width of 8.1±0.1 μm in the X-direction and 7.1±0.1 μm in the Y-direction. The residual width consists of the DEPFET resolution, the intrinsic telescope resolution and a multiple scattering error[1]. Using a GEANT simulation, the error due to multiple scattering and intrinsic telescope resolution is determined to be 6.94 μm. Correcting for this, the DEPFET resolution is 4.2 μm in the X-direction and 1.5 μm in the Y-direction.
In figure 2 the efficiency and purity are shown as a function of the seed cut. The efficiency is defined as the ratio of number of clusters found over the the number of good tracks. A cluster is accepted when it is within ±2 pixels around the predicted position. This yields an efficiency of 99.75% for a 5σ seed cut. Most of the missed clusters are missed because the tracks are scattered too much. Applying a very modest χ^2-cut to remove the worst scattered tracks, the efficiency at a 5σ seed cut increases to 99.96%. The purity is defined as the number of clusters which correspond to a track, over all clusters. At a 5σ seed cut, the purity is around 97%. Increasing the seed cut to 7σ both the efficiency and purity are close to 100%. Note that the most probable signal for seeds is around 60σ.

3.2 Zero-suppression

It is essential during ILC operation to reduce the data volume. Therefore, zero suppression capability was implemented in the readout chip. In the laboratory, the zero-suppressed readout capability of the DEPFET system was demonstrated using a laser spot. In figure 3 an event display with and without zero suppression is shown while illuminating part of the sensor using a laser. The vertical lines are caused by injecting charge in those columns. The horizontal lines in the zero suppressed event display are caused by a common mode fluctuation. The zero-suppression is currently under study in the testbeam.

4 Performance of a DEPFET vertex detector

Next to the R&D on the device, a large (phsyics) simulation study is underway. The DEPFET is implemented in MOKKA[2]. The digitization is done using MARLIN; here Landau fluctuations, charge transport, charge sharing and diffusion, the Lorentz shift and electronic noise are simulated. The correspondence between the testbeam results and the device simulation is excellent, see figure 4. The simulation yields an impact parameter resolution, parametrized by $\sigma^2 = a \otimes b/p_T sin^{3/2}\theta$, at the ILC in a 3T magnetic field with a=2.4 μm and b=7.2 $\mu m GeV/c$, see figure 5, which is better than the ILC requirement of

[1]Note that the multiple scattering error is significant since the beam consists of 6 GeV/c electrons.
[2]A GEANT4-ILC package.

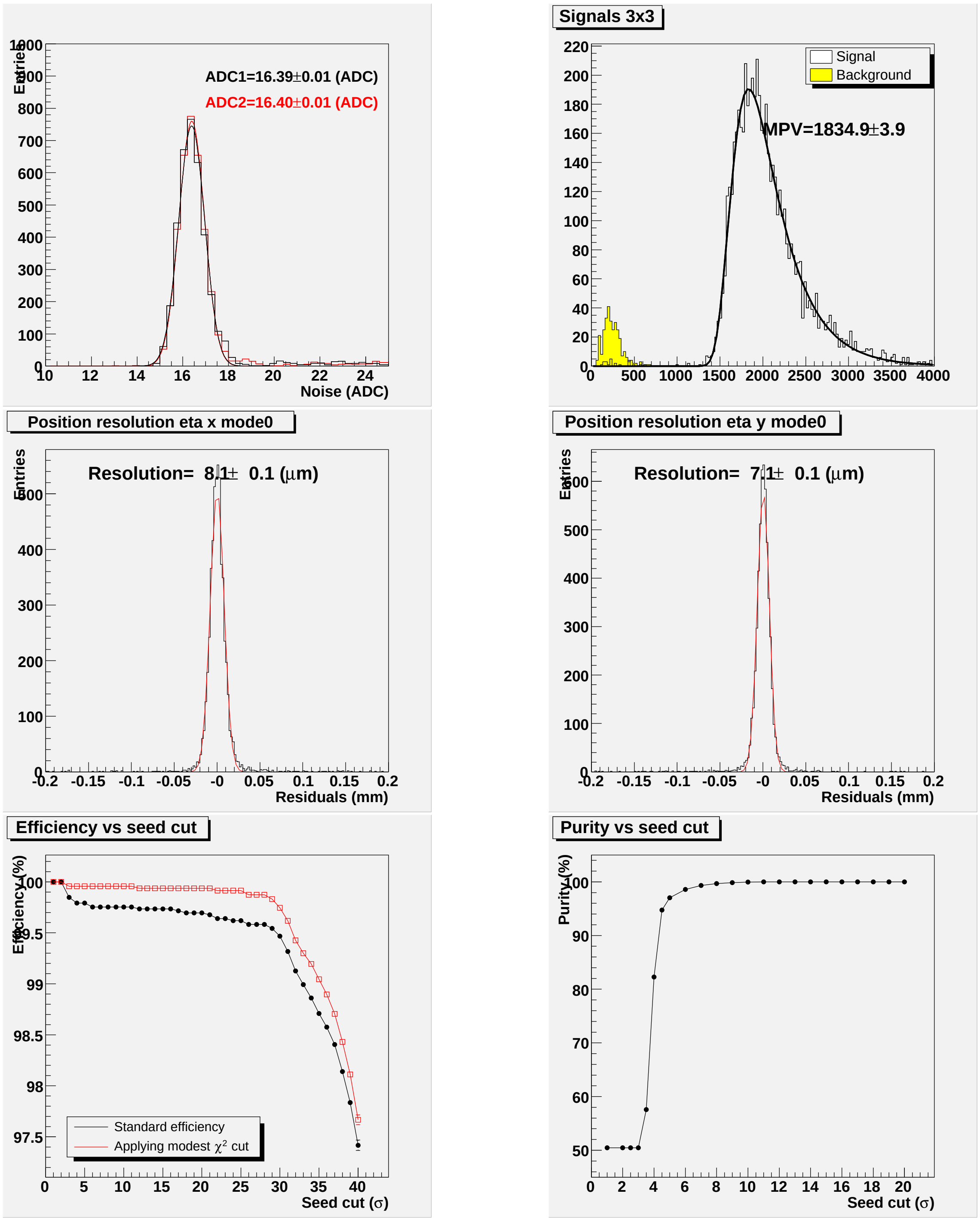

Figure 2: *Noise, signal, residual distributions in the X and the Y direction using the η-algorithm. Efficiency and purity as a function of the seed cut.*

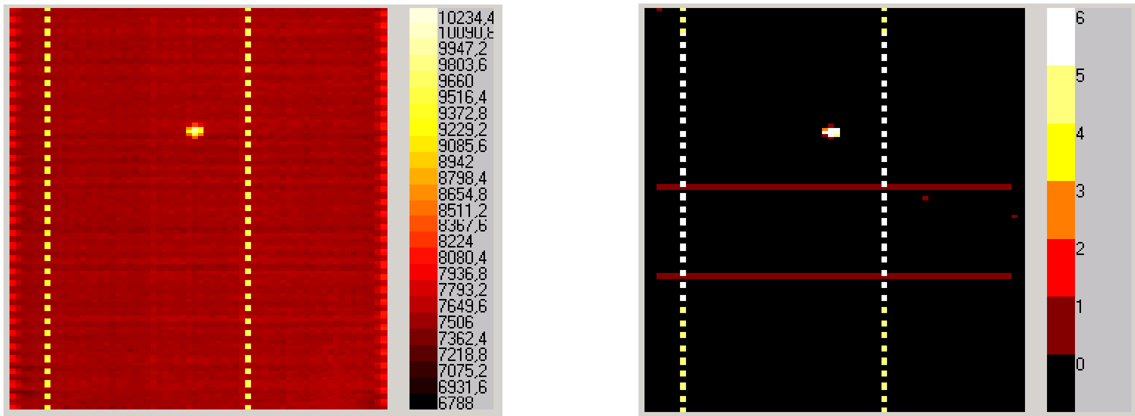

Figure 3: *Raw DEPFET image (left) and after zero suppression (right). Clearly visible are the laser spot and the two columns where charge was injected.*

a <5 μm and b <10 μm.

5 Summery

The DEPFET program is in full swing. Many of the ILC requirements have already been addressed.
The DEPFET was tested in a testbeam with 6 GeV/c electrons. The S/N for the 450 μm thick detector was found to be larger than 110. The position resolution is smaller than the required 5 μm. At a seed cut of 7σ, the efficiency and purity are both ≈100%.
In the readout chip a zero suppression capability has been implemented. The functionality using a laser set up was demonstrated. The performance of the zero suppression is currently being tested in a testbeam.
The predicted performance of a DEPFET based vertex detector, obtained from a simulation where the DEPFET testbeam performance is implemented, is very good.
New large size DEPFET structures are currently being produced. For the final ILC vertex detector, 512×4096 pixels DEPFETs are needed. In the current production 512×512 and 128×4096 pixel devices are being produced.
Currently, the analysis of a high energy testbeam is in progress.

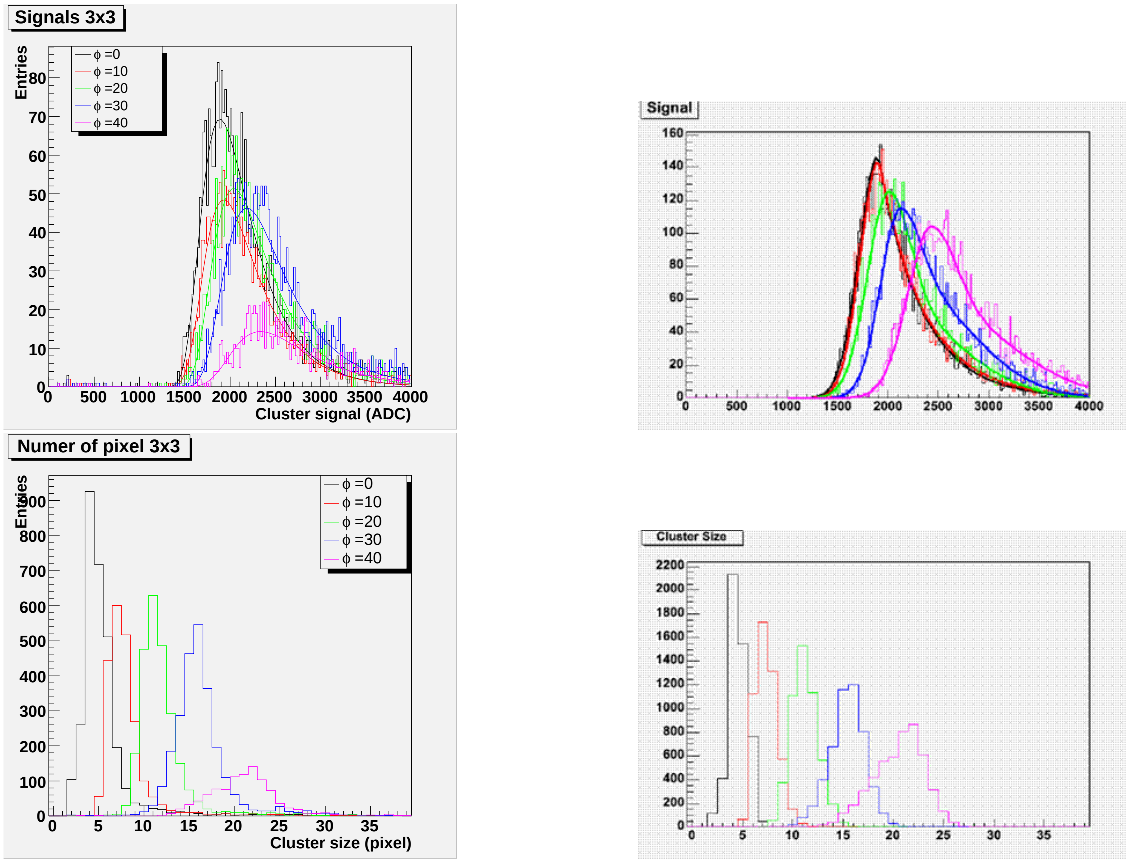

Figure 4: *Comparison of testbeam results and simulation of the 450 μm thick detector in the testbeam using the same MOKKA+MARLIN package that is used for the DEPFET vertex detector performance study. On the left Landau and cluster size distributions measured at various angles of incidence, on the right the same distributions from the simulation.*

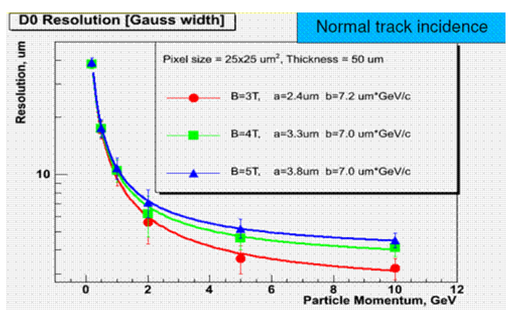

Figure 5: *Impact parameter resolution as a function of the particle momentum for various magnetic field strengths using the DEPFET parameters as planned to be built for the ILC. The same colours are the same angles.*