Development of a B-Factory Monolithic Active Pixel Detector – The Continuous Acquisition Pixel Prototypes–

M. Barbero[1a], G. Varner[1], A. Bozek[2], T. Browder[1], F. Fang[1], M. Hazumi[3], A. Igarashi[4], S. Iwaida[4], J. Kennedy[1], N. Kent[1], S. Olsen[1], H. Palka[2], M. Rosen[1], L. Ruckman[1], S. Stanic[4], K. Trabelsi[1], T. Tsuboyama[3], K. Uchida[1]

***Abstract*--Future vertex detection at an upgraded KEK-B Factory, currently the highest luminosity collider in the world, will require a detector technology capable of withstanding the increased track density and the larger radiation exposure. Near the beam pipe the current silicon strip detectors have projected occupancies in excess of 100%. Advances in Monolithic Active Pixel Sensors (MAPS) look very promising to address this problem. These devices are also quite attractive due to the possibility of making them very thin – essential for improved tracking and vertexing in the low momenta environment of a B-Factory. In the context of the Belle vertex detector upgrade, the major obstacles to realizing such a device have been concerns about radiation hardness and readout speed. Two prototypes implemented in the TSMC 0.35 μm process have been developed to address these issues. Denoted the Continuous Acquisition Pixel, or CAP, the two variants of this architecture are distinguished in that CAP2 includes an 8-deep sampling pipeline within each 22.5 μm^2 pixel. Experience with this deep sub-micron process indicates tolerable threshold voltage shifts for ionizing radiation in excess of 20Mrad. In order to maintain low occupancy and insensitivity to radiation-induced increased leakage current, Correlated Double Sampling with a 10μs frame period is needed. Device description, hit resolution and irradiation results are presented.**

I. INTRODUCTION

MONOLITHIC Active Pixel Sensor (MAPS) prototypes are currently being developed in several efforts worldwide ([1],[2] for example). They are similar to the more standard hybrid pixel detectors, which are the baseline for the experiments at the future LHC [3], in that sense that they provide a detector of very fine granularity with information treatment at the pixel level. In contrast to conventional hybrid pixel detectors [4] (or Si-strip detectors) however, the charge is collected by diffusion in a region ~10 μm thick (no high voltage is needed). These detectors can hence be thinned. They are thus better matched to the context of a Super-B Factory where particles are of relatively low momentum.

At present time, the KEKB accelerator [5] is the highest luminosity collider in the world, and the innermost layer of the current Silicon Vertex Detector of Belle [6] reaches high levels of occupancy. Radiation damage close to the interaction point is also a major issue. So far CCD-based detectors [7] stay radiation soft despite great effort to improve their radiation hardness and this technology is hence not viable for a Super-B Factory. MAPS cumulate the advantages of a better radiation-hardness than the CCD-based pixel detectors (as well as a potential fast processing of the information recorded, as will be shown later in this paper) and the fact that they are not as massive as hybrid pixel detectors.

A pair of MAPS prototype devices has been developed in the context of a Super-B Factory upgrade. In this paper, after an introduction to the operation principal of MAPS detectors and to the Continuous Acquisition Pixel 1 (CAP1) prototype, first test beam results will be given. Irradiation data will be shown. A second CAP prototype (CAP2) has been developed to handle the high data rate and its operation will be described. Finally, a first concept of what a prototype Super-B Factory Pixel Vertex Detector (PVD) could be will be given.

II. THE CONTINUOUS ACQUISITION PIXEL 1 PROTOTYPE

The CAP1 concept is quite simple and was intended to give our group first experience with MAPS detectors. We used the basic 3-transistor pixel cell illustrated in Fig. 1. When the gate of transistor M2 is held to a positive voltage relative to the surrounding well and substrate, electrons created in the sensor are collected and induce a voltage change on the gate of M2. As irreducible leakage current in the sensor eventually causes the collection potential to be lost due to negative charging, a periodic reset must be applied to M1 to restore this collection capability. M3 finally is just used as an output select when reading pixel level out to a row bus.

Manuscript received October 28, 2004.

[1] University of Hawaii, Department of Physics and Astronomy, Watanabe Hall, 2505 Correa Road, Honolulu, Hawaii 96822.

[2] H. Niewodniczanski Institute of Nuclear Physics, Polish Academy of Science, ul. Radziekowskiego 152, 32-342 Krakow Poland.

[3] KEK, High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba-shi, Ibaraki-ken, 305-080 Japan.

[4] University of Tsukuba, 1-1-1 Tenodai, Tsukuba-shi, Ibaraki-ken, 305-8573 Japan

[a] Corresponding author: marlon@phys.hawaii.edu

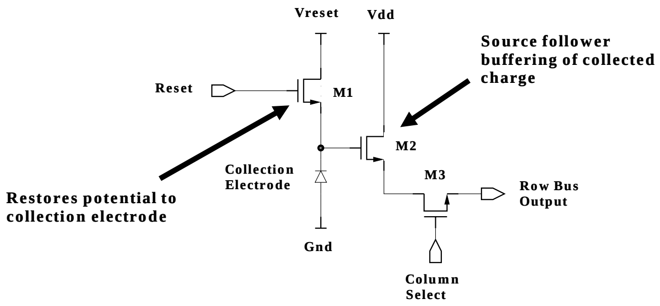

Fig. 1. The simple 3-transistor cell, which is the base of the CAP1 detector.

We built an array of about 6k pixels out of this base structure, organized in 132 columns and 48 rows (shown in Fig. 2) plus some infrastructure to read as fast as possible. Noise in the CAP1 detector could be lowered down to about 16e- rms. The leakage current of the un-irradiated detector is approximately 320 pA.cm^{-2}.

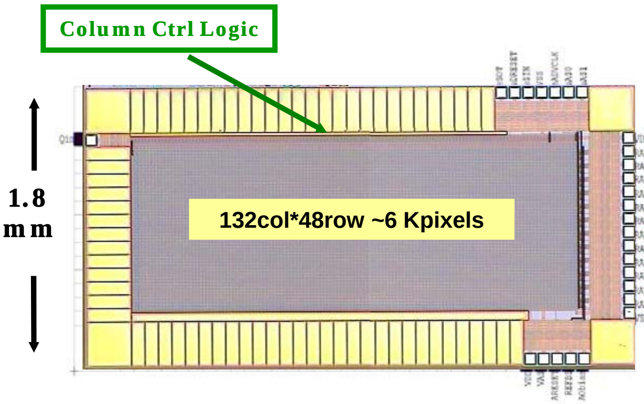

Fig. 2. The 6336 pixel CAP1 array. Note that the CAP2 array of section V is built of the same number of rows x columns.

A readout system was developed with the goal of reading out the CAP1 prototype, keeping in mind that it could be adapted with minimal effort to the CAP2 readout. The CAP detector is part of a Front-End board which consists of a CAP carrier (for handy insertion / removal of specific CAP prototypes), some multiplexers, a 10-bit ADC, and a serializer. From the serializer, the signals are converted to LVDS. A pair of RG45 cables is used for data transmission between the Front-End and the Back-End board, as well as for communication of various signals and power. Signals needed for the CAP operation as well as for the operation of blocks of the Front-End board are programmed from an on-board Xilinx CPLD. Fig. 3 shows a block diagram of the Front-End board.

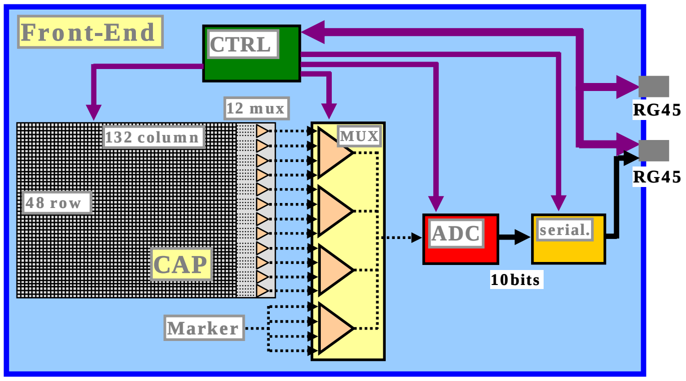

Fig. 3. Block diagram of the Front-End board used for CAP1 / CAP2 readout.

Four Front-End boards communicate in parallel with the Back-End board which is powered inside a compact PCI crate. The Back-End board consists of a de-serializer, some RAM, a PLX chip to communicate with a CPU for event processing. Each of the four detector channels is handled by a 'Buffer' CPLD. Synchronization between the four channels as well as global system control is provided by a fifth Back-End board "CTRL" CPLD. Overview of the system is given in Fig. 4.

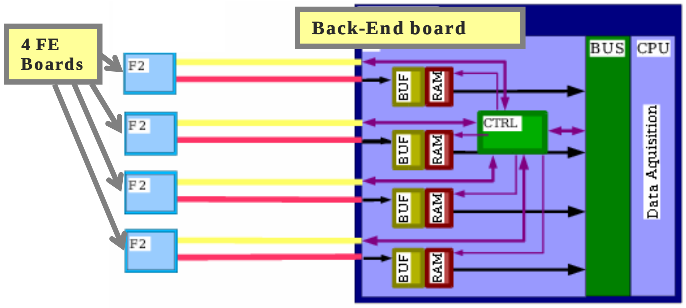

Fig. 4. System overview. The four Front-End boards communicate in parallel with the Back-End board sitting in the compact PCI crate.

Some software was developed to handle the data acquisition and the readout from the RAM. It does Correlated Double Sampling and leakage current subtraction, and provides some Signal to Noise Ratio (SNR) information for each pixel of each CAP detector.

III. TEST BEAM RESULTS

In June 2004, a first beam test of the CAP prototypes was done in KEK, Tsukuba, Japan. The beam delivered consisted of pions of momentum ranging from hundreds of MeV/c to ~ 4 GeV/c. After a first phase of smooth setting-up of the system (four CAPs system described in section II), data taking took place for approximately 10 days. The system was remarkably stable during operation, apart from grounding problems due to AC power fluctuations in the test area.

That first measurement pursued was the determination of the hit resolution of the CAP sensor. The four detectors were aligned in the beam line. A scheme of the setup used is shown in Fig. 5 (distances and material are given there).

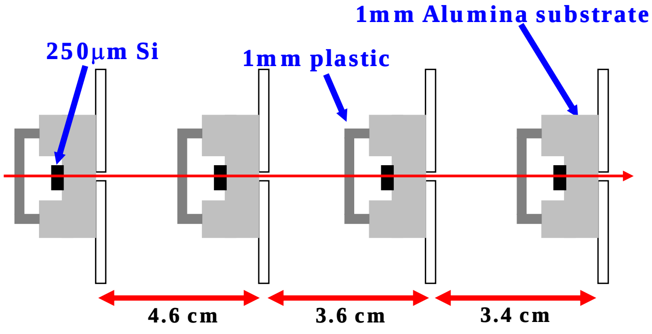

Fig. 5. Scheme of the setup of the June 2004 test beam. Note the distances and material used.

A first data sample is taken and an alignment procedure is triggered in software including translations and rotations of the four detectors (to correct for misalignment). Once corrections for misalignment are taken into account, a second data sample is acquired with pions of 4 GeV/c momentum. Residuals are calculated: the Gaussian fit to the residuals shown in Fig. 6 exhibits a standard deviation of about 11 μm, which gives an upper limit on the hit resolution.

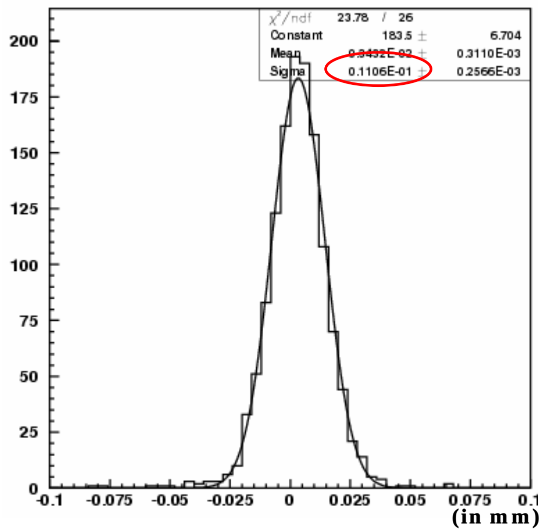

Fig. 6. Gaussian fit to residuals for 4 GeV/c momentum pions (horizontal axis is given in mm).

This measurement will be improved in a future test beam where access to higher momentum particles will be provided (based upon simulations, we expect the spatial resolution of the 22.5 μm^2 CAP pixels to be in the order of 2 to 3 μm).

Other measurements pursued included a study of the charge spread in the CAP sensor. When a particle crosses the CAP sensor, electron-hole pairs are generated in the ~ 10 μm thick epitaxial layer and electrons are collected in about 100-200 ns. The question of the charge spreading in the CAP is important for the development of efficient clustering algorithms. In Fig. 7, the percentage of the charge collected is given as a function of the number of pixels included in a cluster.

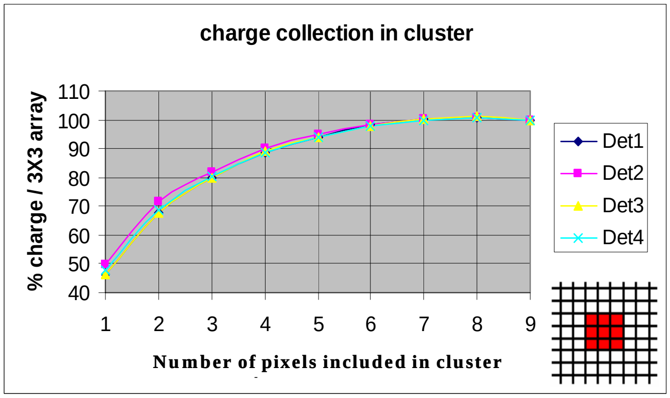

Fig. 7. Charge collection in the four CAP1 sensors during the June 2004 test beam: percentage of charge collected as a function of the number of pixels included in the cluster (MPV of Landau fit).

As a starting hypothesis, we considered that all the charge was collected in a 3x3 pixel array around the pixel of highest SNR, as this was suggested by previous studies performed taking into account larger pixel array (5x5 and 7x7). The fact that the percentage of the charge collected seems to saturate already when we include 6 pixels or more corroborate this hypothesis. The values given are Most Probable Values of a Landau fit to the Signal distribution. We found that approximately 50% of the charge is collected in the peak SNR pixel and about 90% of the charge is collected in the four main pixels (added in descending order of their recorded signals). This measurement can be related to other works which can be found in the literature ([8] for example, where a similar measurement with a MAPS in a 0.6 μm process, 15 μm thick epitaxial layer, leads to 40% of the charge collected in the main pixel and 80% within four pixels).

IV. SUMMARY OF IRRADIATION STUDIES

To withstand the harsh environment of a Super-B Factory, future vertex detectors must be very radiation hard. High level of radiation is one of the reasons which rules out the use of CCD-like detectors. Despite intrinsic reasons which tend to make one think that MAPS detectors are potentially more capable of withstanding radiation, the radiation hardness of MAPS detectors needs to be studied and demonstrated. Gamma irradiation (^{60}Co) of the CAP1 detector has been performed to four landmark doses: 200 kRad, 2 MRad, 3 MRad and 20 MRad. Annealing of the devices after irradiation in various conditions tried to mimic the natural annealing the detectors would encounter in the experiment. A summary of the leakage current measurements done as a function of the radiation dose is given in Fig. 8.

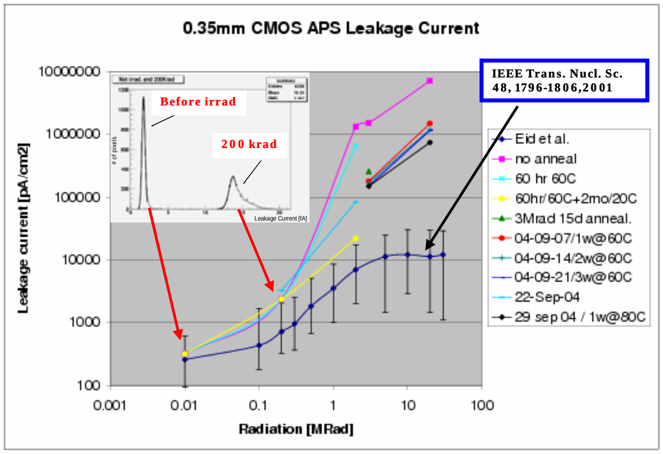

Fig. 8. Leakage current (given in $pA.cm^{-2}$) as a function of the radiation dose for ^{60}Co irradiation (given in Mrad). Comparison is provided with measurements in a similar 0.35μm process using the techniques of enclosed transistor layout and guard-rings [9].

The measurements shown in Fig. 8 were performed at room temperature. As an inset, we have shown the measurement of the leakage currents before irradiation and after 200 kRad. Note the increase of the tail of the leakage current distribution for the 6336 pixels after 200 kRad. The CAP1 leakage current is less than 320 $pA.cm^{-2}$ before irradiation, and increases by factors ~8, ~4200, ~4800 and ~22500 for 200 kRad, 2 MRad, 3 MRad and 20 MRad respectively, before annealing. The effect of annealing in various conditions is also shown in Fig. 8. One can see that after annealing, the leakage current decreases by at least an order of magnitude for the 2 MRad, 3 MRad and 20 MRad CAP detectors.

It is important to note that up to 20 MRad, survival of the functionalities of the detectors could be shown. It is not clear if the saturation of the leakage current observed by other groups [9] above a couple of MRad was reproduced or not. It should finally be underlined that the reduced SNR due to the increase of noise after irradiation could be shown to be acceptable even for the 20 MRad irradiated detector. The only concern is the degradation of the charge collection due to the creation of trapping sites in the irradiated sensor. Operation with heavily irradiated sensors still needs to be demonstrated and this will be studied at a future beam test. Depending on the outcome of these tests, technical changes to the CAP prototype series could then be considered.

V. READOUT SPEED AND FIRST DETECTOR CONCEPT

In the CAP1 prototype, to be able to perform Correlated Double Sampling, the pixels must be continuously read out, disregarding the presence of a trigger. The reading out of the pixel data is a time consuming process, which was further amplified by the fact that the pixel data were analyzed "on the fly" to be recorded if the SNR of a pixel exceeded a tunable threshold (self-triggered recording mode). For an 8 ms integration time, the live time of the CAP1 detector array was on the order of 16%.

A second prototype, CAP2, was designed in order to enhance the live time of the CAP by recording data in an 8-deep pipeline in each pixel cell. The trigger can then be externally provided, the integration time can be drastically reduced, and the live time of the detector depends then only on the trigger frequency, taking also into account that about 1ms is needed for each frame read out. Fig. 9 shows the CAP2 pixel cell schematic.

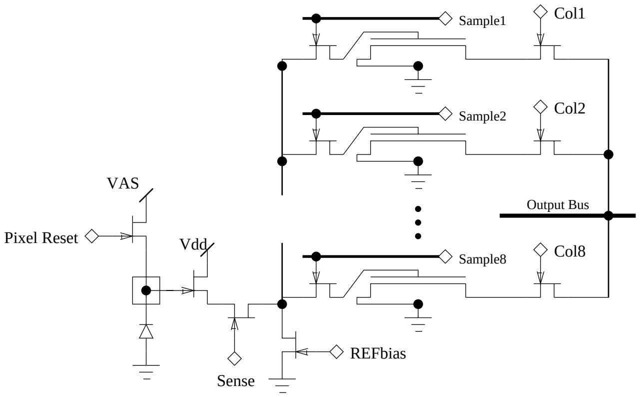

Fig. 9. Schematic of a pixel cell in CAP2. An 8-deep mini-pipeline is implemented in each pixel cell after the basic CAP1-like 3-transistor structure.

A new firmware and data acquisition program were written to handle the more complex operation of CAP2. We investigated a 15μs frame acquisition time with CAP2. The CAP2 prototype shows an increased noise (30 electrons noise measured) compared to CAP1. The mini-pipeline output level dispersion is quite large within the pixels, which underlines the need for 8 separate look-up tables for the 8 possible buffer transitions. At present, further work is still being performed on the CAP2 prototype characterization.

Meanwhile, the design of a CAP3 prototype has started in the framework of a first detector concept. CAP3 is designed in the TSMC 0.25 μm process and consists of an array of 128x928 22.5 μm^2 pixels (approx. 120 k-channels per CAP3). The size of the active area of CAP3 is about 3mm x 21 mm. In parallel, a first version of a pixel readout chip, PIXRO1, is designed to handle data transmission between the CAP3 and the laser driver of the optical link. These are the two main building blocks of the half ladder of a first “toy” detector concept. This half ladder is shown in Fig. 10, and a conceptual drawing of a possible detector is shown in Fig. 11.

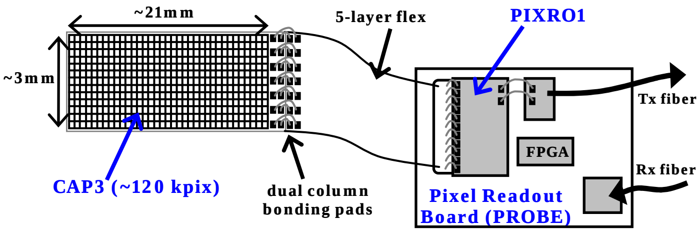

Fig. 10. Schematic of a half ladder. The ~120,000 pixels CAP3 prototype communicates through a 5-layer flex with the PIXRO1 chip which sits on the Pixel Readout Board (PROBE). Data is transmitted and control signals are received through optical fibers.

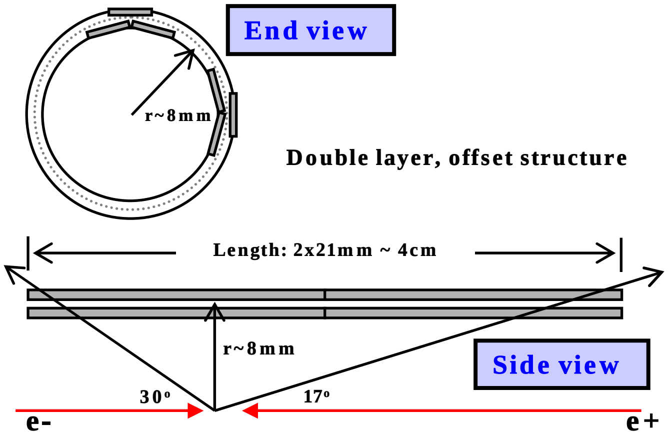

Fig. 11. A first conceptual drawing of a Belle vertex detector using the CAP3 prototype: end view and side view.

Taking into account the foreseen 10 kHz First Level Trigger (L1T) frequency in super-Belle, as well as the 10 µs frame acquisition rate we would like to use (already experienced with CAP2), we can follow the data flow from the CAP3 to the optical fiber and deduce in the next paragraph a number of design constraints on our system.

To take into account the fact that the 10 kHz L1T frequency is an average rate, a 5-deep buffer pair is implemented in each pixel cell. The detector (1 k-columns x 2 samples) must be read out in 100 µs. We have hence 100 ns to read out a single column. Implementing a system of 32 8-to-1 multiplexers at the output, this can be done, provided that we can broadcast data in about 10 ns (taking into account a 20 ns internal bus settling time). Connection from CAP3 to the PROBE is done via a 5-layer flex, with 16 pairs of 100 MHz signals. With 16 differential receivers, the PIXRO1 chip does 16 Correlated Double Samples in parallel, and after some final high speed 16-to-1 analog multiplexing, data is sent out through the analog optical fiber at ~1.6 Giga-Samples per second (6-bit analog equivalent broadcast).

VI. CONCLUSION

Two MAPS prototypes have been developed in the context of a Super-B Factory upgrade. The first one, CAP1, has been evaluated in a test beam. CAP2 was characterized in the laboratory, and will be the subject of a future test beam. Irradiation results were also given. A third prototype is being developed at present, as well as the building blocks of a first detector concept, including a Pixel Readout chip, PIXRO1, which provides connection between the CAP3 detector and the outside.

These results make MAPS a very promising technology for a Super-B Factory upgrade.

VII. REFERENCES

[1] R. Turchetta, J.D. Berst, B. Casadei, G. Claus, C. Colledani, W. Dulinski *et al.*, "A monolithic active pixel sensor for charged particle tracking and imaging using standard VLSI CMOS technology", Nucl. Instr. and Meth. A **458** (2001), pp 677-689.

[2] H.S. Matis, F. Bieser, S. Kleinfelder, G. Rai, F. Retiere, H.G. Ritter *et al.*, "Charged particle detection using a CMOS active pixel sensor", IEEE *Trans. Nucl. Sci.*, vol. 50, no. 4, pp 1020-1025, Aug 2003.

[3] "The Large Hadron Collider, conceptual design". CERN-AC-95-05 (LHC), CERN-ARCH-LHC-3-087.

[4] M. Barbero, W. Bertl, G. Dietrich, A. Dorokhov, W. Erdmann, K. Gabathuler *et al.*, "Design and test of the CMS pixel readout chip", Nucl. Instr. and Meth. A **517** (2004), pp 349-359, and references therein.

[5] S. Kurokawa, E. Kikutani, "Overview of the KEKB Accelerators", Nucl. Instr. and Meth. A **499** (2001), and other papers in this volume.

[6] Y. Ushiroda, "Belle Silicon Vertex Detectors" Nucl..Instr. and Meth. A **511** (2003), 6.

[7] C.J.S. Damerell, R.L English, A.R. Gillman, A.L. Lintern, D.Phillips, D.Su *et al.*, "A CCD-Based Particle Detector for SLD", Nucl. Instr. and Meth. A **288** (1990), pp 236-239.

[8] G. Claus, C. Colledani, W. Dulinski, D. Husson, R. Turchetta, J.L. Riester *et al.*, "Particle tracking using CMOS monolithic active pixel sensor", Nucl. Instr. and Meth. A **465** (2001), pp 120-124.

[9] E-S Eid, T.Y. Chan, E.R. Fossum, R.H. Tsai, R. Spagnuolo, J. Deily *et al.*, "Design and Characterization of Ionizing Radiation-Tolerant CMOS APS Image Sensors up to 30 Mrd (Si) Total Dose", IEEE *Trans. Nucl. Sci.*, vol. 48, no. 6, pp 1796-1806, Dec 2001.