Small-Scale Readout System Prototype for the STAR PIXEL Detector

M. Szelezniak [a,b], A. Besson [b], C. Colledani [b], A. Dorokhov [b], W. Dulinski [b], L. Greiner [a], A. Himmi [b], C. Hu [b], H. S. Matis [a], A. Rose [a], A. Shabetai [b], T. Stezelberger [a], X. Sun [a], J. H. Thomas [a], I. Valin [b], C. Q. Vu [a], H. Wieman [a], M. Winter [b]

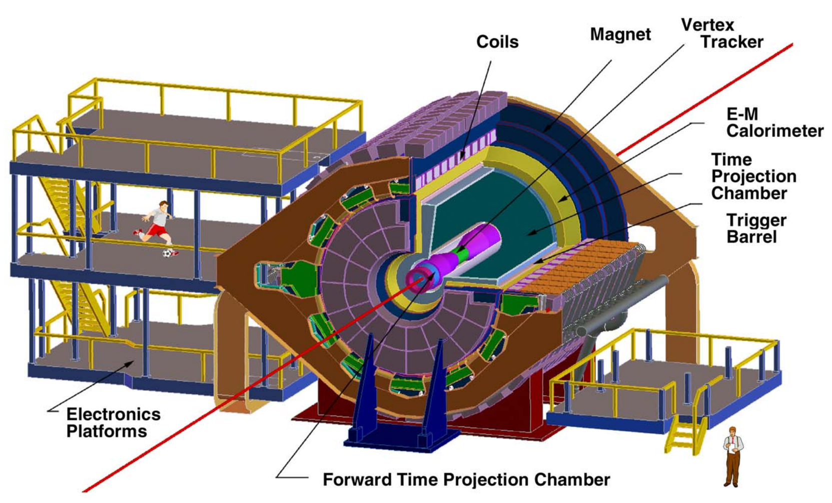
[a] LBNL, 1 Cyclotron Road, Berkeley, CA 94720, USA

[b] IPHC, 23 rue de Loess, BP28, F-67037 Strasbourg, France

Abstract

A prototype readout system for the STAR PIXEL detector in a Heavy Flavor Tracker vertex detector upgrade is presented. The PIXEL detector is a Monolithic Active Pixel Sensors (MAPS) based silicon pixel vertex detector fabricated in commercial CMOS process that integrates the detector and front-end electronics layers in one silicon wafer. MAPS prototypes designed specifically for the PIXEL are discussed. The readout architecture for the PIXEL has been recently prototyped in a telescope system consisting of three small size MAPS sensors arranged into three parallel and coaxial planes. The proposed readout architecture is simple and scales to the size required by the final detector. The real-time cluster finding algorithm necessary for data rate reduction in the 135 mega pixel detector is described, and aspects of the PIXEL system integration into the existing STAR framework are addressed. The complete system has been recently tested and shown to be fully functional.

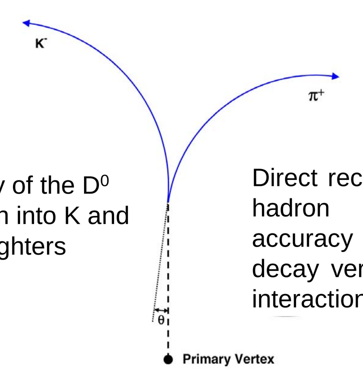
New Vertex Detector for STAR



STAR detector at the Relativistic Heavy Ion Collider (RHIC) located at Brookhaven National Laboratory, USA

Purpose:
- Direct topological reconstruction of charm
- New physics:
  - Charm flow to test thermalization at RHIC
  - Charm energy loss to test pQCD in a hot and dense medium

PIXEL characteristics:
- Two layers at 2.5 & 7 cm radius (9+24 ladders)
- Nearly 135 M pixels
- 0.28 % radiation length/layer
- Air cooled
- Quick extraction and sensor replacement
- Monolithic Active Pixel Sensors
  - Thinned to 50 µm thickness
  - 30 µm x 30 µm pixels
  - 640 x 640 pixel array

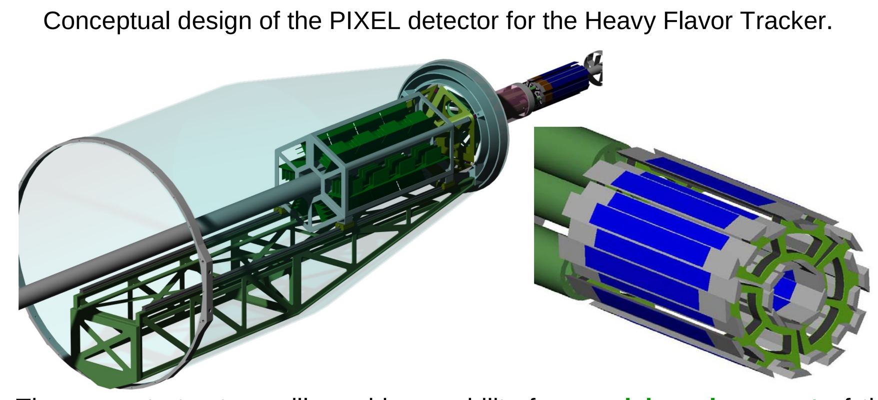


Decay of the D^0 meson into K and π daughters

Direct reconstruction of a charmed hadron requires high track accuracy to identify the secondary decay vertex from the primary ion interaction.

PIXEL pointing at the collision vertex: ~ 30 µm

Conceptual design of the PIXEL detector for the Heavy Flavor Tracker.

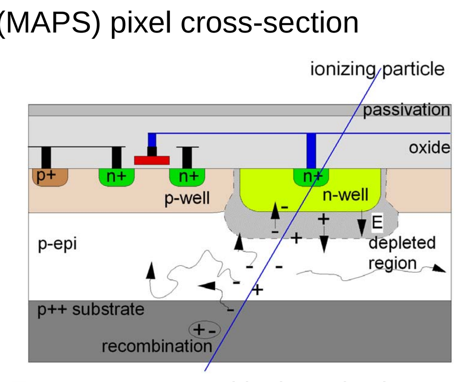


The support structure will provide capability for a **quick replacement** of the detector with a very high accuracy positioning.

Reference:
- T.J. Hallman et al., **Experimental and theoretical challenges in the search for the quark-gluon plasma: The STAR Collaboration's critical assessment of the evidence from RHIC collisions,** Nuclear Physics A, vol. 757 (2005), pp. 102-183
- A. Rose (for the STAR Collaboration), **The STAR Heavy Flavor Tracker**, J. Phys. G: Nucl. Part. Phys. 34 (2007) S715–S718

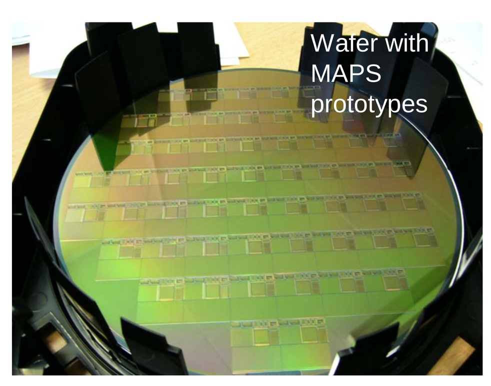
Monolithic Active Pixel Sensors (MAPS) Technology

Monolithic Active Pixel Sensors (MAPS) pixel cross-section



Electrons generated in the epitaxial layer thermally diffuse until they reach low potential in the n-well region.

Properties:
- Signal created in low-doped epitaxial layer (typically ~10 µm)
- Charge sensing in n-well/p-epi junction
- Charge collection mainly through thermal diffusion (~100 ns), reflective boundaries at p-well and substrate
- Sensor and signal processing integrated in the same silicon wafer
- Standard commercial CMOS technology
- High granularity
- Fast readout, low noise, low power dissipation
- Satisfactory radiation tolerance
- Thinning available as standard post-processing

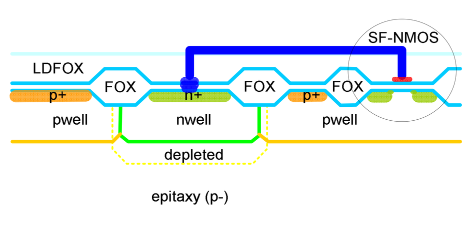


Maximum sensor size is limited by process masks to a full-reticule (app. 2×2 cm²)

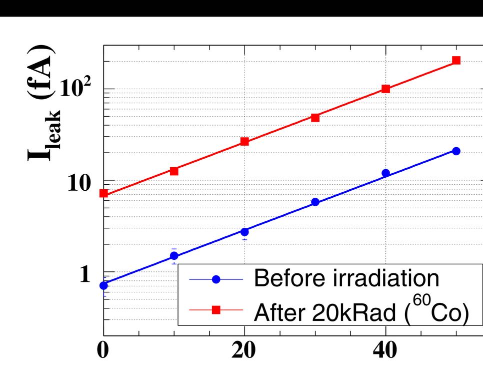
Reference: G. Deptuch, **New generation of monolithic active pixel sensors for charged particle detection,** PhD thesis, Universite Louis Pasteur, Strasbourg, 2002

MAPS Development for STAR

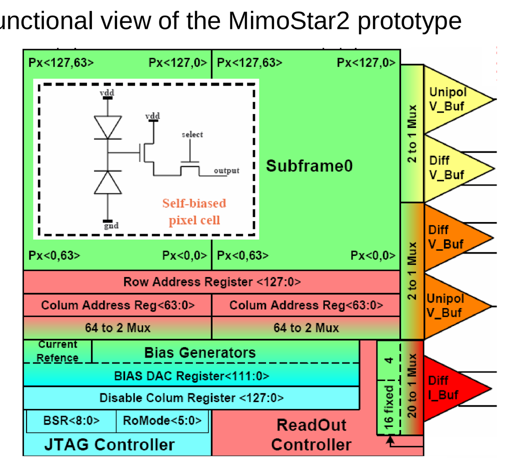
A first generation MAPS prototypes for STAR:
- **Radiation tolerant diode design**
- **Analog readout**
- **JTAG controlled configuration**

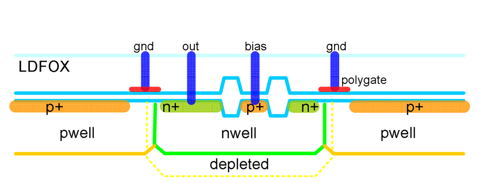


standard diode layout

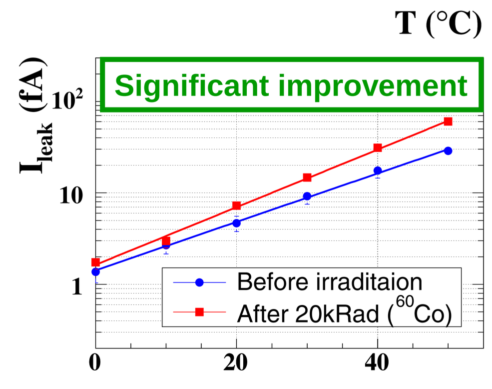


Functional view of the MimoStar2 prototype

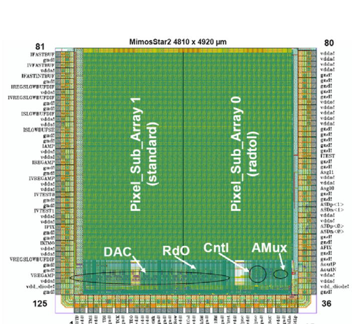


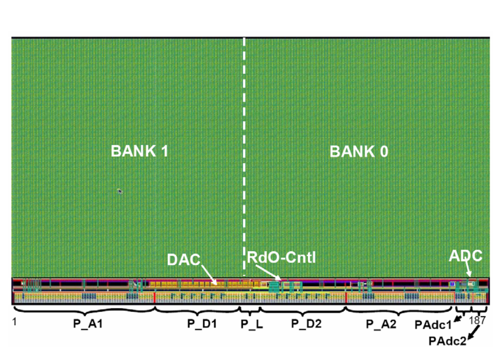


thin-oxide diode layout



MimoStar2
128×128 pixels
30 µm pixel pitch





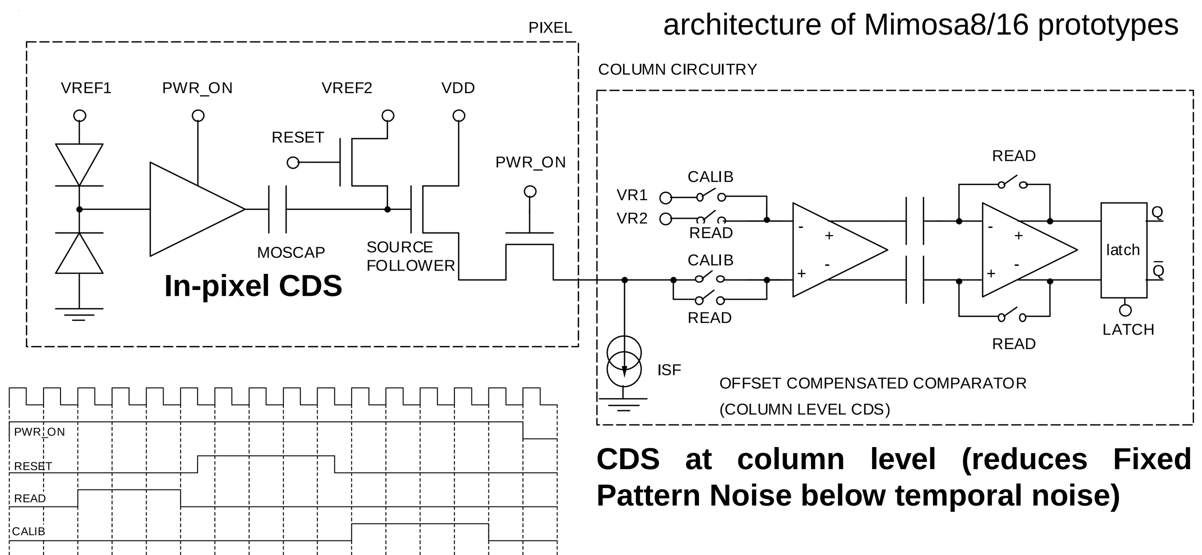
MimoStar3
320×640 pixels, 30 µm pixel pitch
Low yield – under investigation

MimoStar2 performance at 30°C and 4 ms integration time (non irradiated chip):

Noise	16 e⁻
S/N (MPV)	14
Detection efficiency	99.7±0.06 %

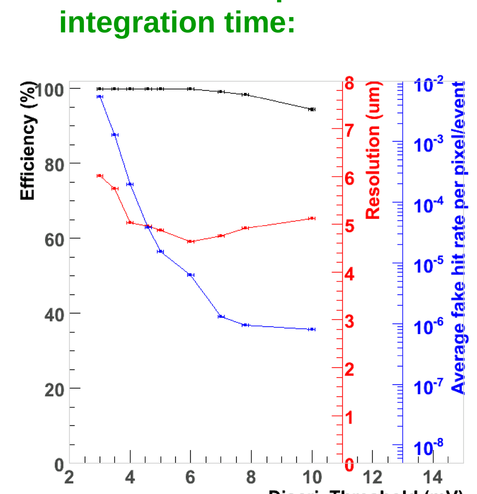
Next generation :
- **Radiation tolerant diode design**
- **Column parallel readout with on-chip discriminators**
- **Binary readout**
- **JTAG controlled configuration**
- **On-chip zero suppression** (currently at prototyping stage)

architecture of Mimosa8/16 prototypes



CDS at column level (reduces Fixed Pattern Noise below temporal noise)

Mimosa16 performance at 20°C and 50 µs integration time:



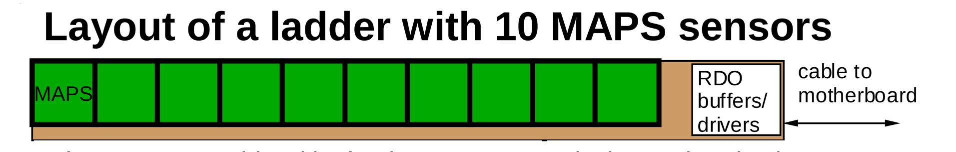
See also poster N24-254: Binary Mode CMOS Sensors for MIP Detection

Reference:
- W. Dulinski et al., **Optimization of Tracking Performance of CMOS Monolithic Active Pixel Sensors,** IEEE Transactions on Nuclear Science, vol. 54, no. 1, 2007
- Y. Degerli et al., **A Fast Monolithic Active Pixel Sensor With Pixel-Level Reset Noise Suppression and Binary Outputs for Charged Particle Detection,** IEEE Transactions on Nuclear Science, vol. 52, no. 6, 2005

Ladder Structure for PIXEL Detector

Early prototype ladder equipped with MAPS. A Kapton cable with 4 copper conductor layers was used to deliver signals to the edge of the ladder.

Layout of a ladder with 10 MAPS sensors



PIXEL detector serviced by a multiple parallel readout system.

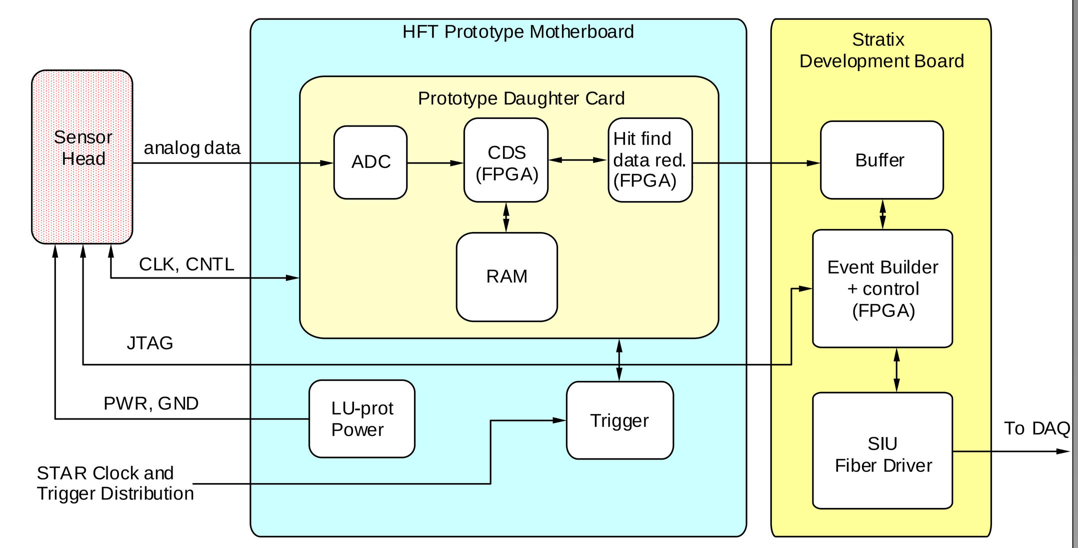
Prototype Readout System with On-the-fly Zero Suppression

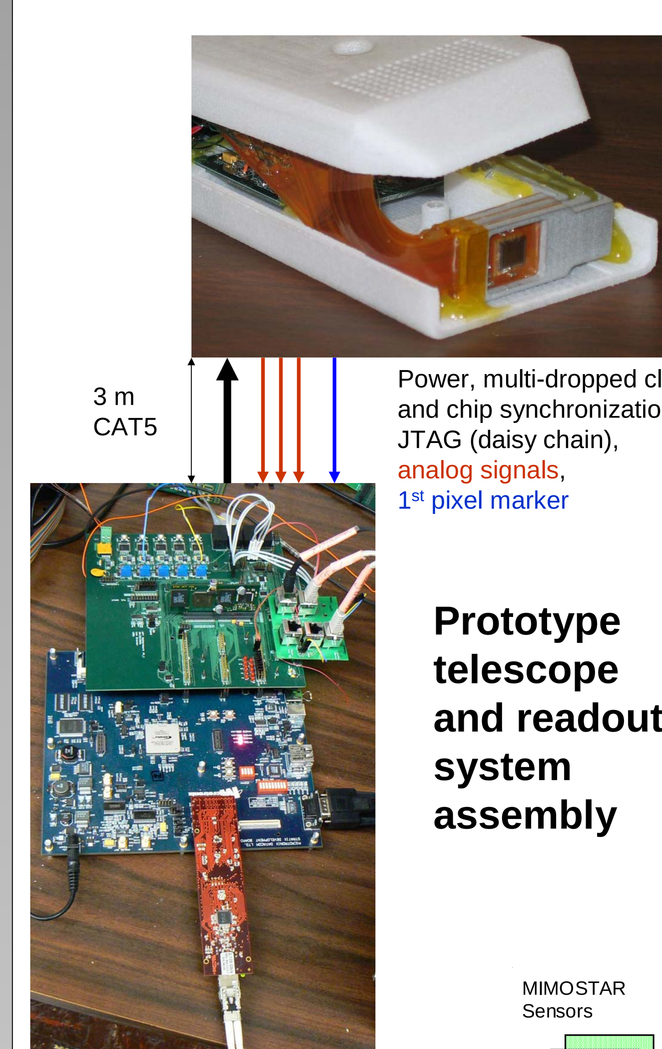
The MimoStar2 telescope readout system is a small size prototype. All elements of the implemented readout chain can be scaled up to accommodate the complete PIXEL detector system.

Purpose:

To test the functionality of a prototype MimoStar2 detector system in the STAR environment during the 2006-2007 run:
- Charged particle environment near the interaction region in STAR
- The noise environment in the area in which we expect to put the final PIXEL
- Performance of the MimoStar2 sensors
- Performance of our cluster finding algorithm
- Performance of our hardware/firmware as a system
- Functionality of our interfaces to the other STAR subsystems

Functional block diagram of the prototype PIXEL readout system



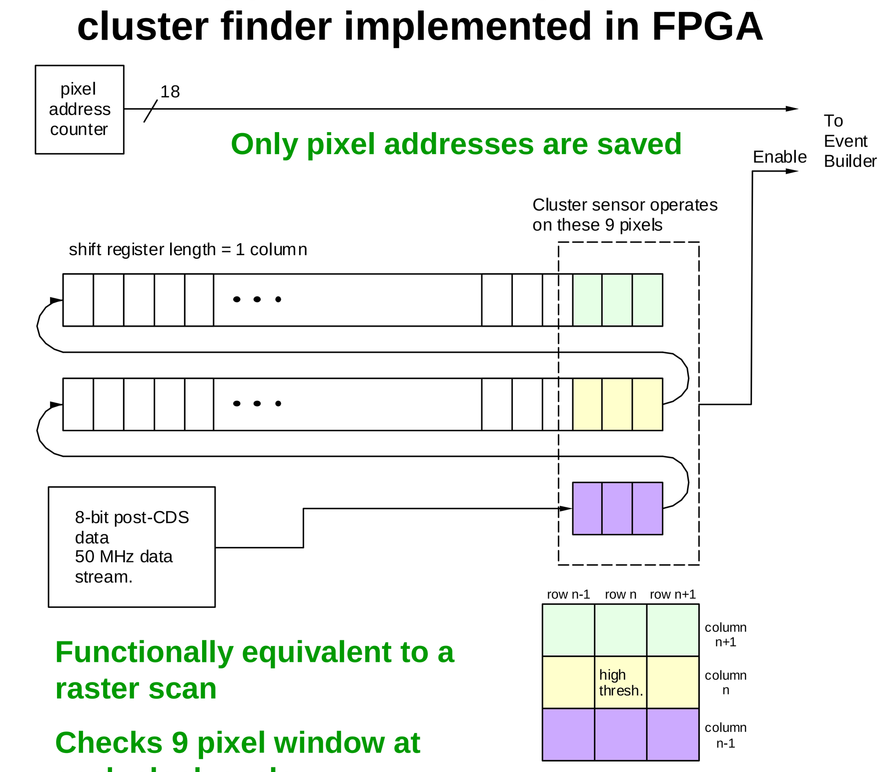


Power, multi-dropped clock and chip synchronization, JTAG (daisy chain), analog signals, 1st pixel marker

Prototype telescope and readout system assembly

Fully formed events, with a header that contains a unique trigger ID, are sent out to the Linux-based acquisition PC through a fiber optic connection.

Zero suppression through on-the-fly cluster finder implemented in FPGA

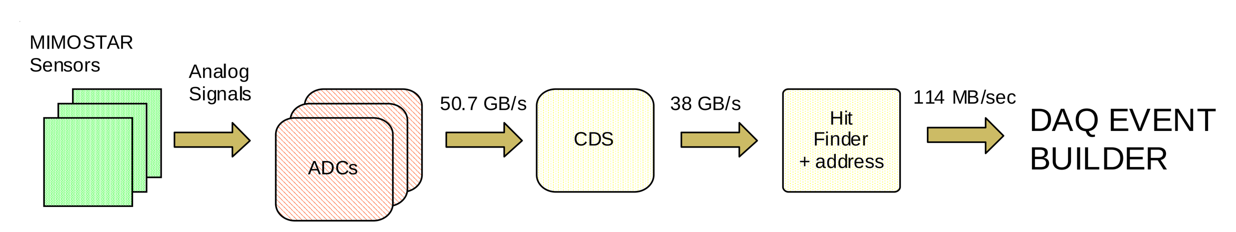


Functionally equivalent to a raster scan

Checks 9 pixel window at each clock cycle

Hits are recognized when:
- signal in the central pixel exceeds high threshold
- and any one of the neighboring 8 pixels exceeds low threshold.

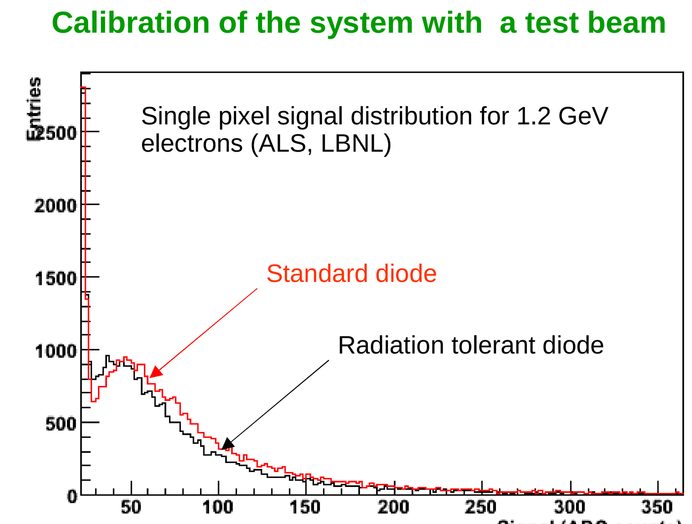
Efficiency and accidental rates are comparable to the traditional ADC sum method.



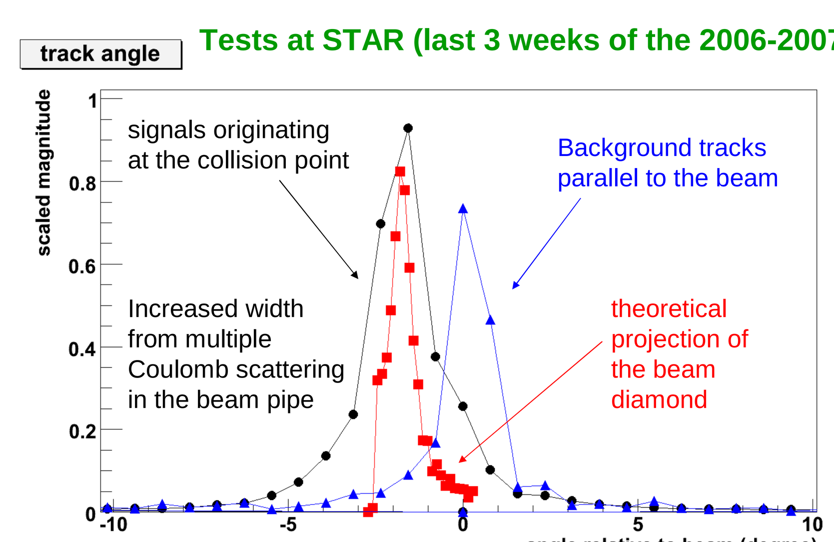
Expected nearly 3 orders of magnitude data flow reduction in the complete PIXEL detector.

Test Results with the Prototype Readout System

Calibration of the system with a test beam



Tests at STAR (last 3 weeks of the 2006-2007 run at RHIC)



Telescope location: 5 cm below the center of the beam pipe and at 145 cm distance from the collision point.

- Measured charged particle flux was ~ 3.9 merged clusters per sensor (1.7 µs integration time, L=8×10²⁶ cm⁻²s⁻¹).
- Noise level of setup in the STAR environment was ~35 electrons*, comparable to laboratory and ALS measurements.
- TLD measured dose at head position, 325 rad over running time. This scales to an integrated dose of several hundred krad/run.

* Elevated noise resulted from un-bonded pads that correspond to outputs of the sensors' internal DACs

Conclusions

- RDO system with on-the-fly data sparsification implemented and functional for Mimostar2 sensors.
- Prototype system fully functional and characterized.
- Fully functioning interfaces between the prototype system and STAR detector infrastructure.
- Completed measurements of detector environment at STAR.

Acknowledgments

We gratefully acknowledge the assistance of David Malone and Warren Byrne at the ALS, Bob Souza and Ken Asselta at the STAR hall at RHIC. This work received support in part from the US Department of Energy – Contract no. DE-AC02-05CH11231, Office of Nuclear Physics.