IEEE NSS/MIC 2009
Oct 25-31, 2009
Orlando, Florida

Sensor/IC Integration Using Oxide Bonding

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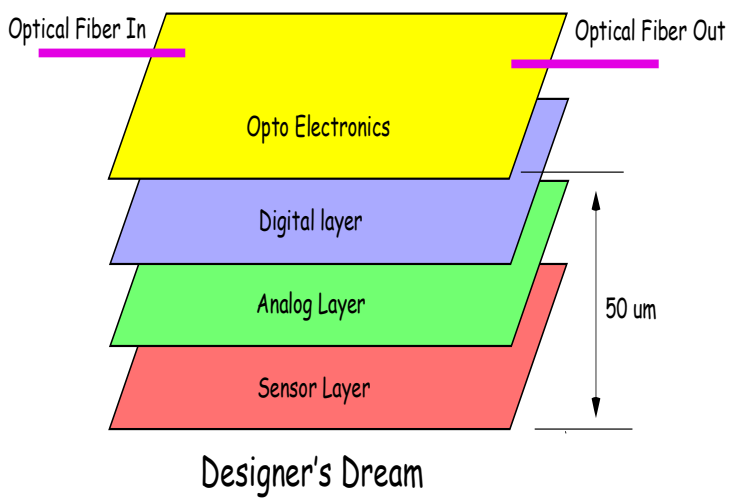
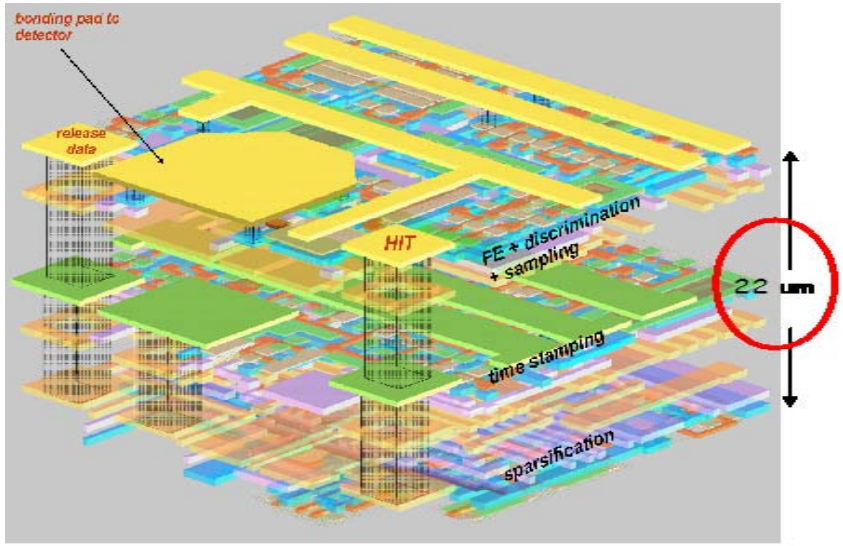
Outline

- **Introduction**
  - 3D IC, Direct Bond Interconnect
- **DBI Prototypes**
  - Edgeless Pixel Sensor
- **Test Results**
  - Sensor Leakage Current
  - Charge Injection Results
  - Response to Laser
  - Responses to Sources
  - Test Beam Tests
- **Conclusion**

Introduction – 3D IC

- A **vertically (3D) integrated circuit** comprised of 2 or more layers of semi-conductor devices which have been thinned, bonded, and interconnected to form a "monolithic" circuit. These layers can be devices made in different technologies.
- The move to 3D is being driven by industry:
  - Reduces trace length; Reduces R, L, C;
  - Improves speed; Reduces interconnect power, crosstalk;
  - Reduces chip size; Processing for each layer can be optimized.





Introduction

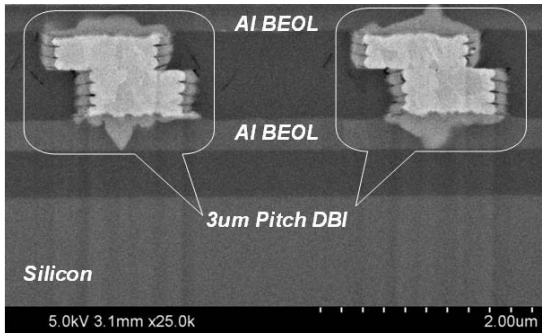
- **3D IC vendors with commercially available bonding process**
  - Tezzaron – Cu-Cu thermo-compression for bonding
  - Zycube – Adhesive and In-Au bump for bonding
  - **Ziptronix - Direct Bond Interconnect**

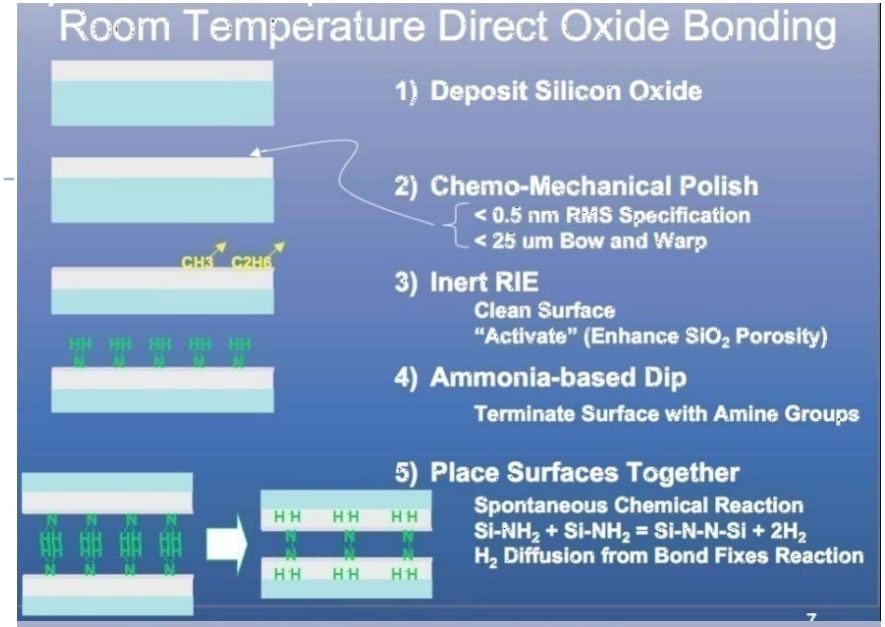
- **Fermilab is working with Ziptronix to demonstrate the DBI technology for particle physics sensor/ROIC integration:**
  - **ultimate goal** – fine pitch (<25 μm) pixel arrays with a sensor layer integrated with one or more layers of electronics with total thickness of less than 100 μm.

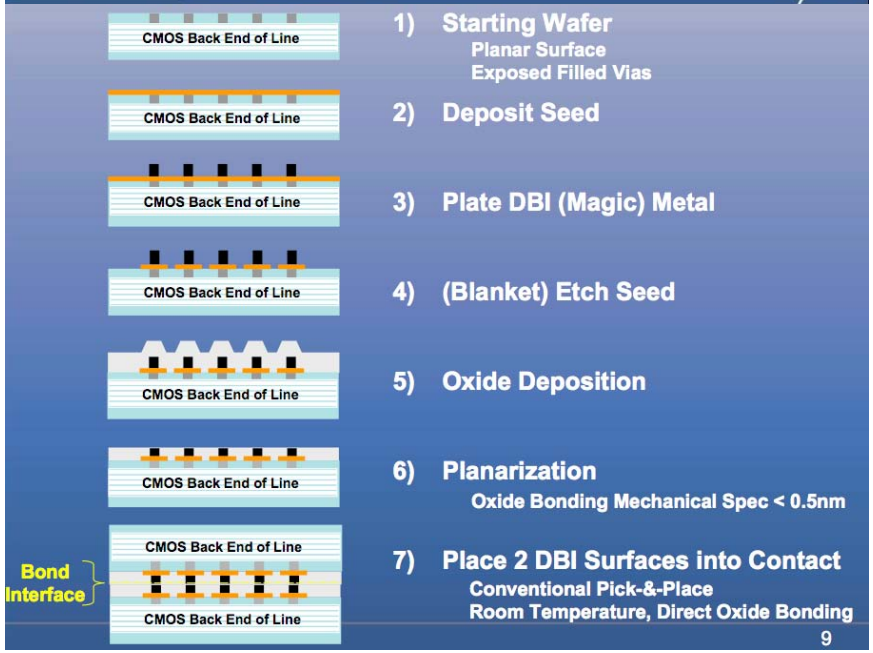
- Fermilab is also working on 3D ROIC R&D (N27-1 G.W. Deptuch).

DBI Technology

- Oxide bonding at room temperature.
- Metal connection by thermo-compression.
- Robust mechanical connection – sensor/IC can be ground and thinned after bonding.
- 3 μm pitch achieved; also Low mass.
- Die to wafer, wafer to wafer.
- ROICs can be placed onto sensor wafers with 10 μm gaps – pave the way towards thinned full coverage detector planes.
- Could be fairly inexpensive (esp. w2w).



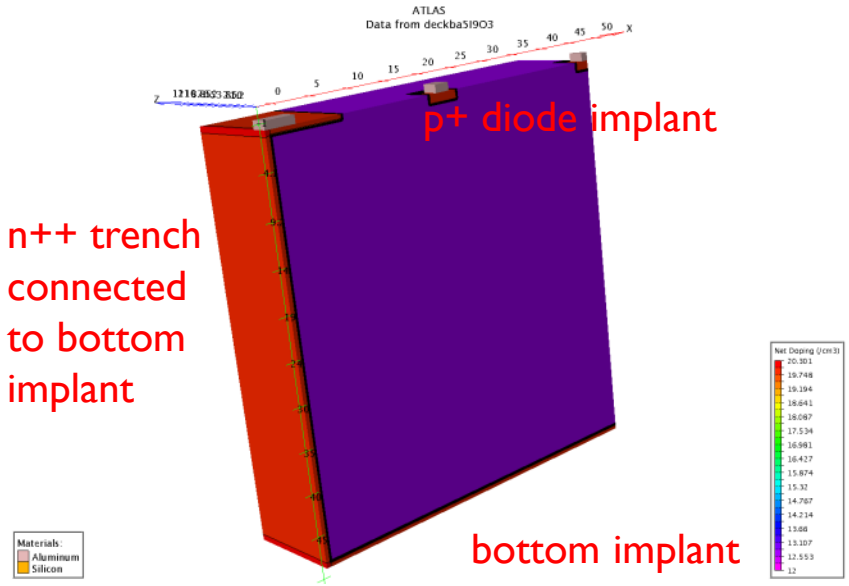




DBI Prototypes

- **Edgeless trenched pixel sensor**:
  - p+ diodes on n- bulk (ρ=5kΩ·cm);
  - 22 column x 128 rows
    - 50x600 μm for 1st and 22nd column
    - 50x400 μm for 2nd-21st column
  - **50 μm deep n++ trench at the edge**:
    - **can use it as a high quality detector edge;**
    - **can use it as an electrode – eliminating edge losses in tiling reticle-sized detectors.**
  - masks designed at Fermilab;
  - fabricated by MIT-Lincoln Lab.

Sensor cross section



DBI Prototypes

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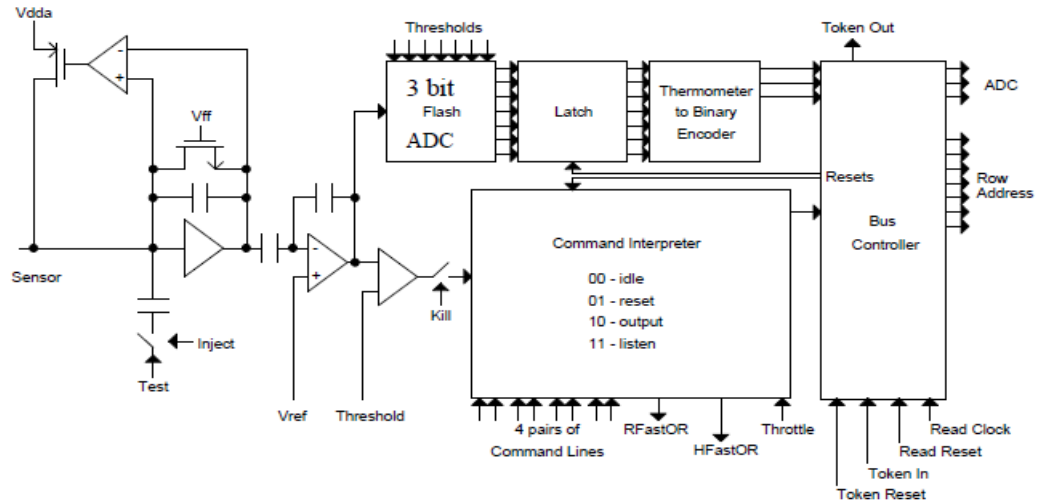
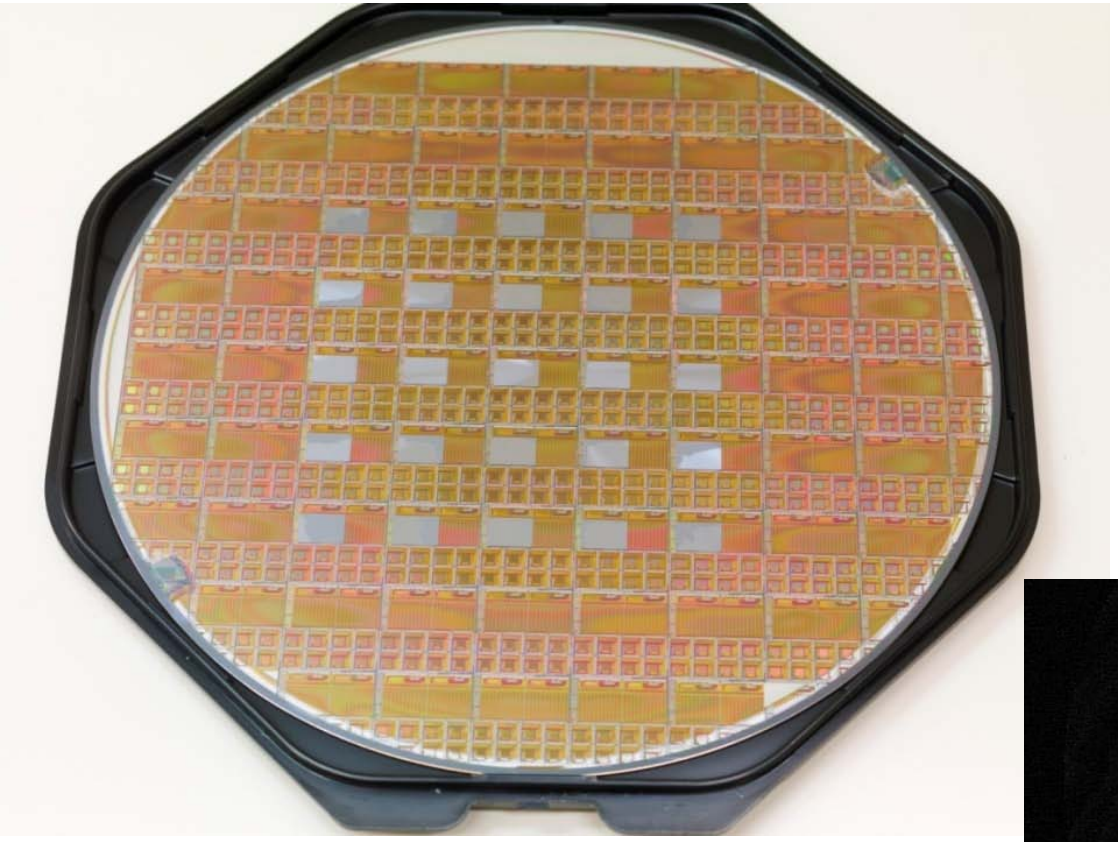
  - 50 μm deep n++ trench at the edge:
  - masks designed at Fermilab;
  - fabricated by MIT-Lincoln Lab.
- **BTeV FPIX2.1 readout chip:**
  - 22x128 (C*R) pixel cells of 50x400 μm;
  - designed for e- signals (3 bits ADC), can work with small hole signals but Y/N only;
  - can inject test pulse to capacitor(~3.5fF);
  - debugging pads available for analog and digital output of the pixels in the last row.



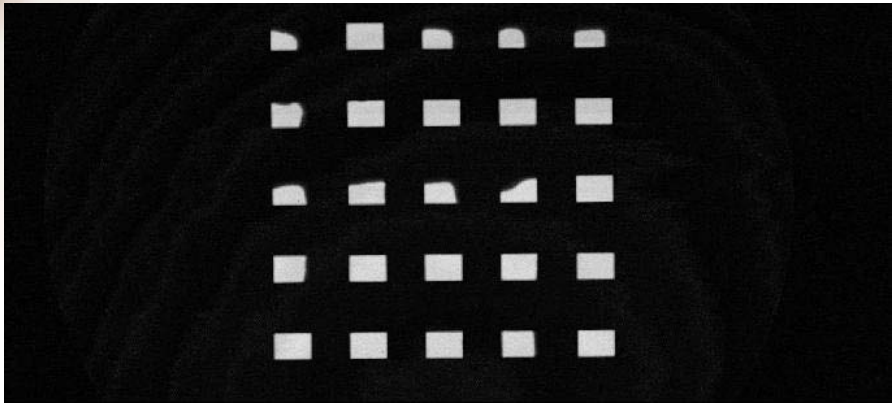
A FPIX2 Pixel Unit Cell

DBI Prototypes



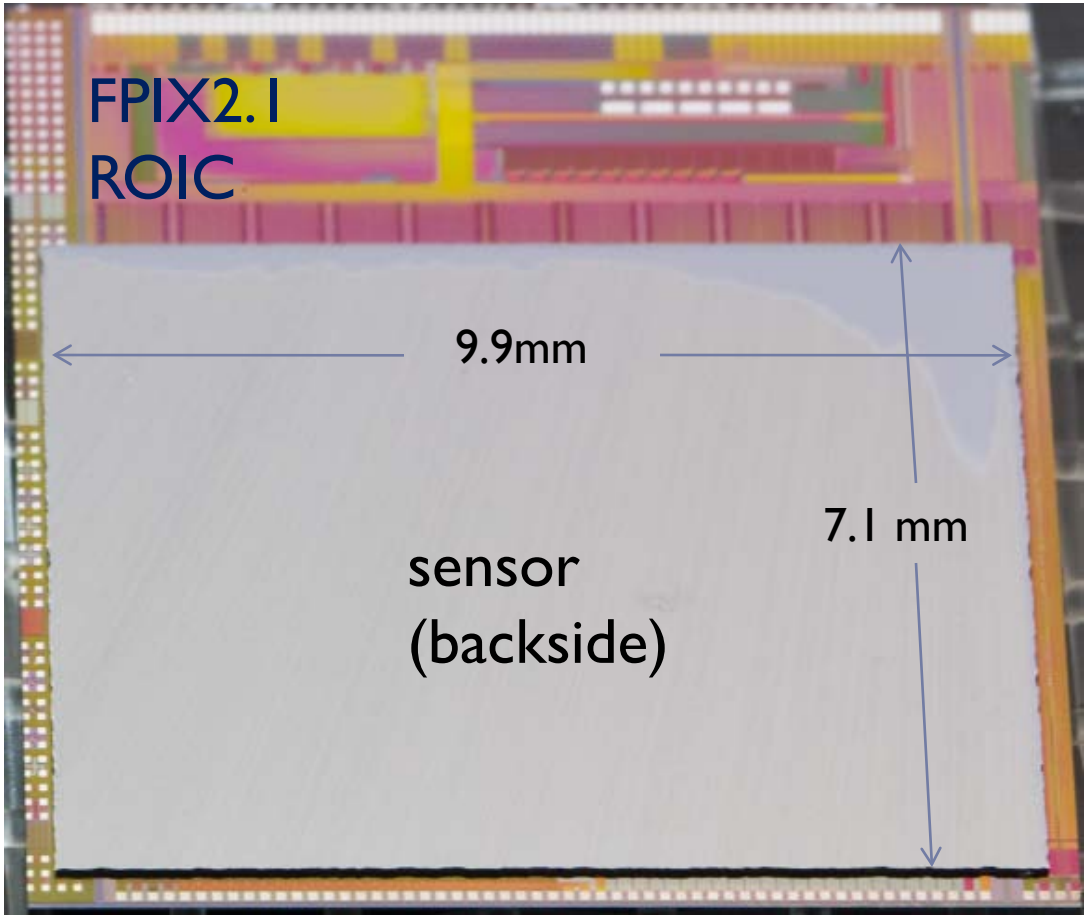
A DBI bonded FPIX wafer by Ziptronix

- 50 MIT_LL sensors DBI bonded to two FPIX wafers by Ziptronix.
- Sensors thinned to 100 μm after bonding, backside not implanted.
- 30 good devices at the end (16 with bond voids indicated by SAM. Normal yield is 80-90% if not dealing with a small number of wafers as us).



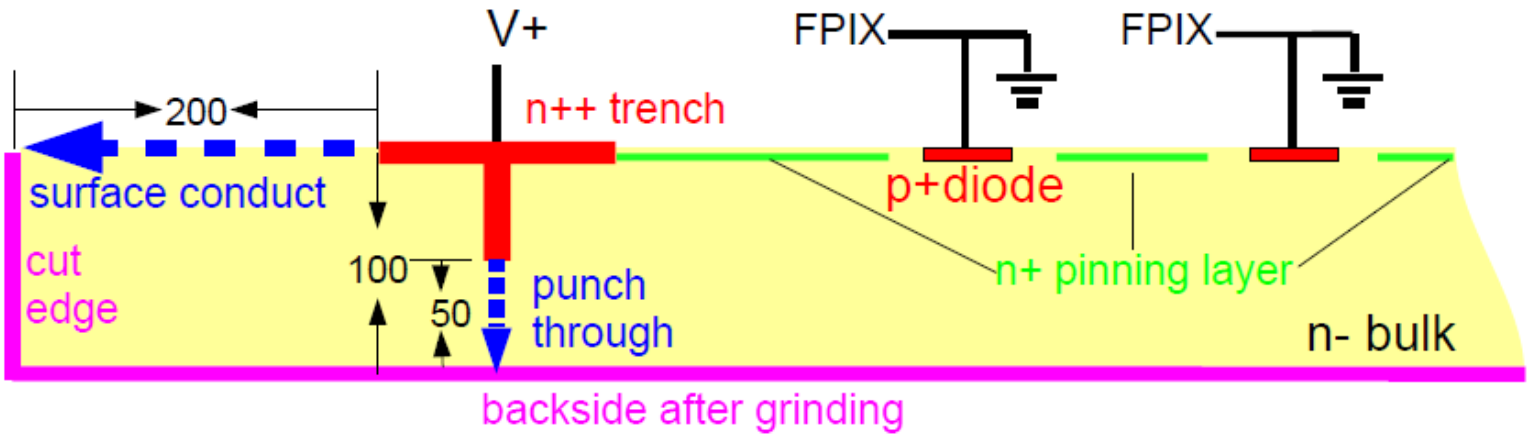
Scanning Acoustic Microscopy

DBI Prototypes



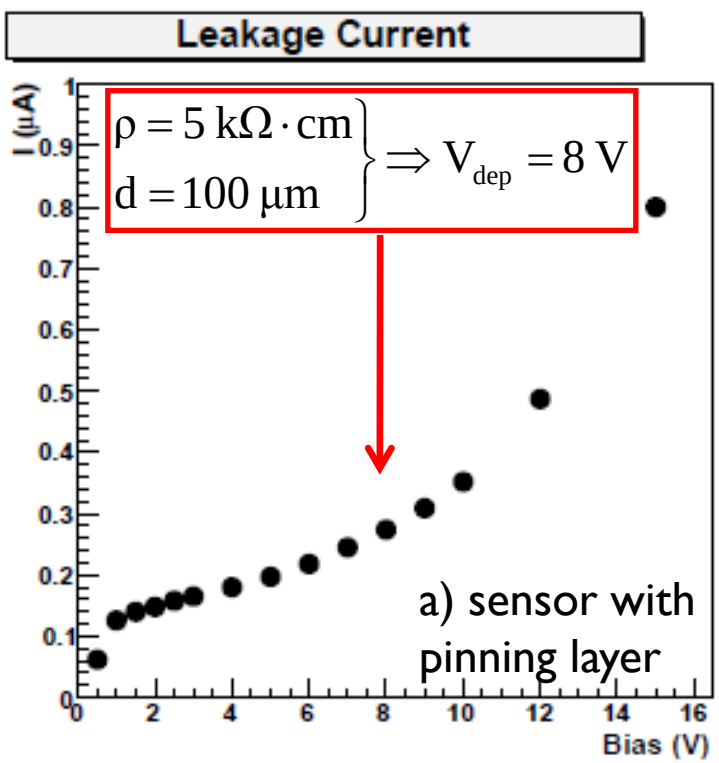
A integrated device after dicing

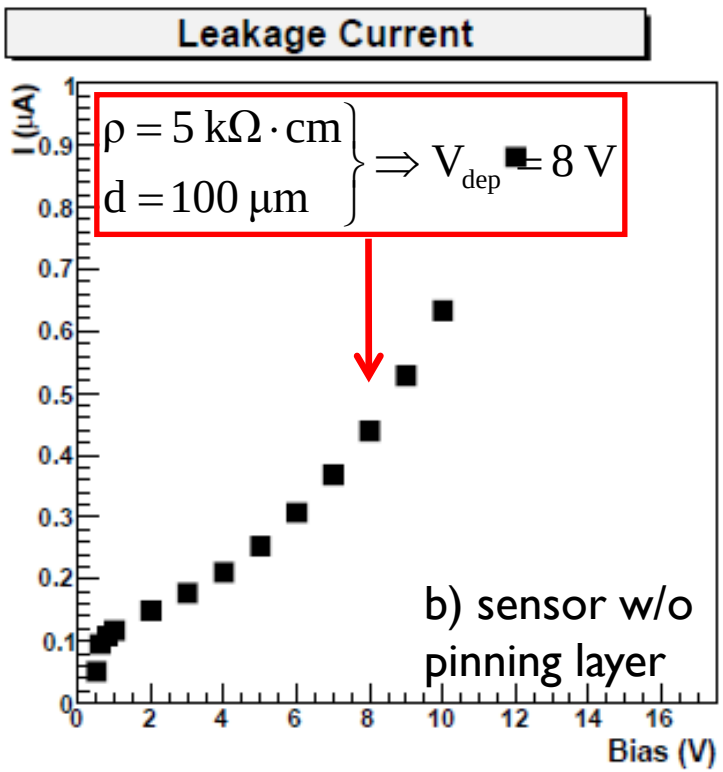
Sensor Bias Scheme



- Sensor bias scheme:
  - p+ diodes (DBI) connected to FPIX input at ground potential;
  - n++ trench (DBI) connected to positive potential through FPIX.
- The electrical connection from the trench to the ground surface of the backside might be either (a) along the surface and cut edge or (b) by punch-through 50 μm bulk.
- (optional) n+ pinning layer surrounding p+ diodes and extended to trench:
  - commonly used in optical devices to passivate the detector surface;
  - could act as a shield between the detector and ROIC.

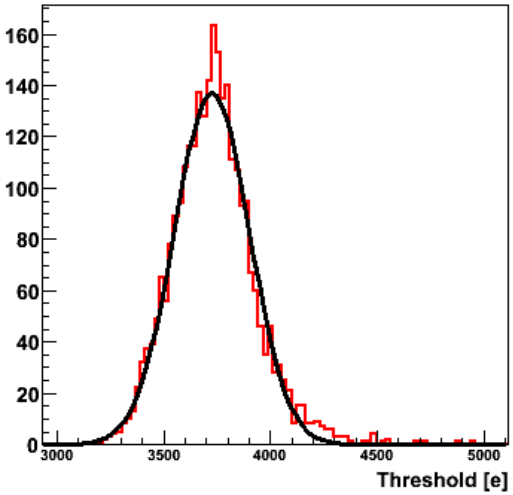
Leakage Current per Chip

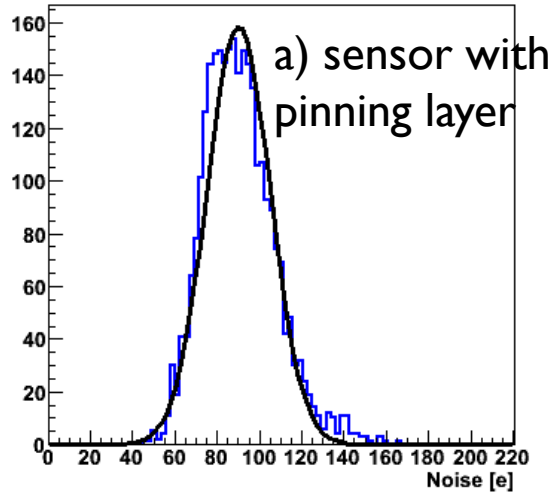


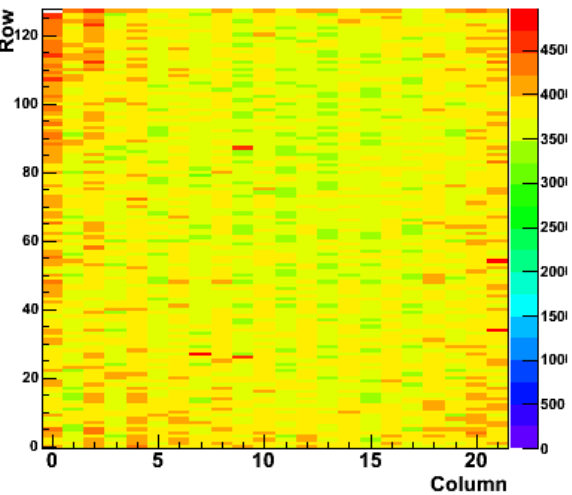


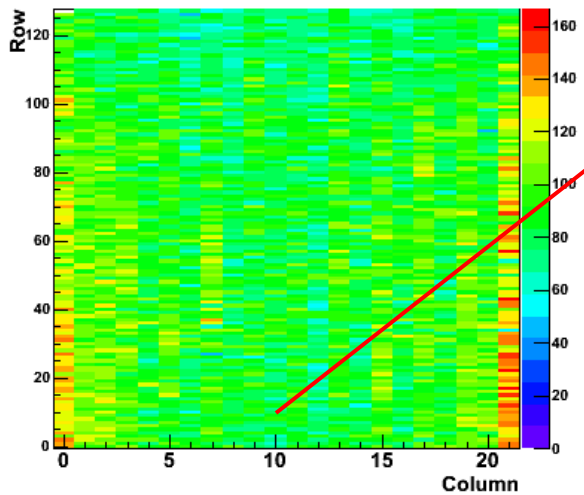
- The rapid increase of the leakage current beyond the full depletion voltage is due to the bare ground backside surface and the associated crystal damages.
- Have sent chips to Cornell to further thin the sensors down to 50 μm (include a fine grind process "near-CMP" quality), backside implant and laser annealing.

Threshold Scan – (e-) Charge Injection

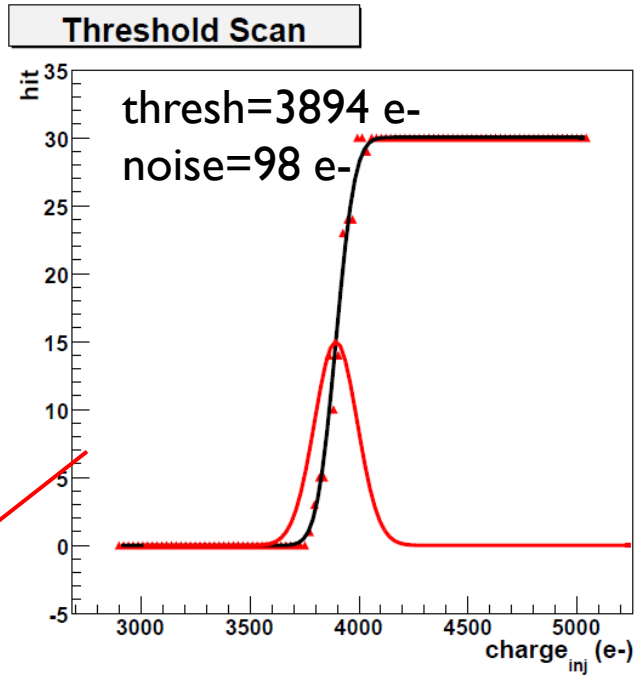






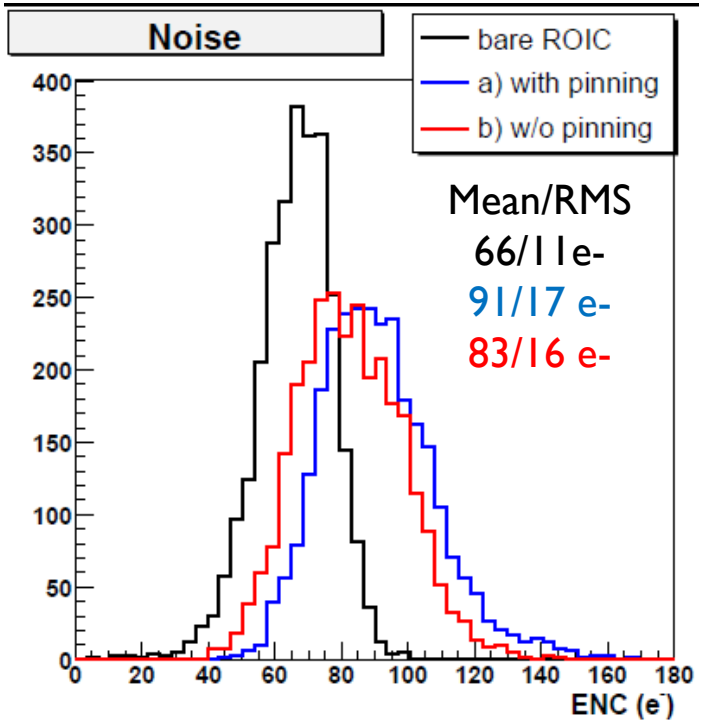


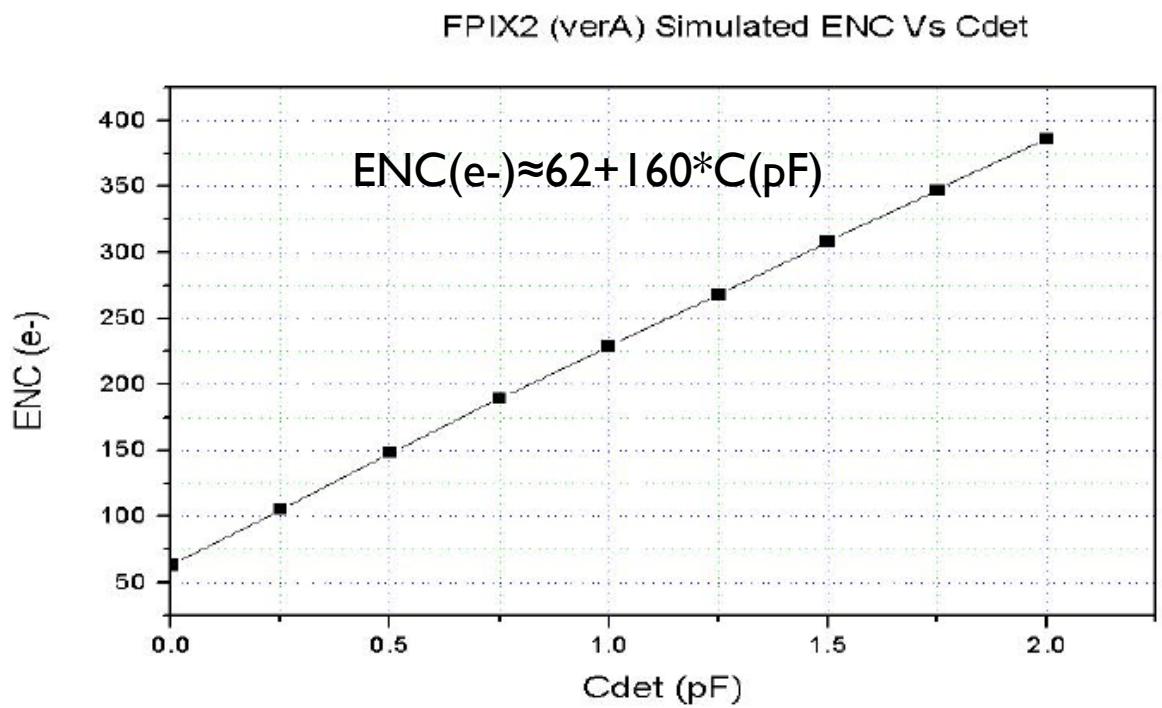
S-curve for pixel (10,10)



Conversion from the test pulse size to the number of electrons done assuming 3.5fF injection capacitors.

Sensor Input Capacitance to FPIX2.1



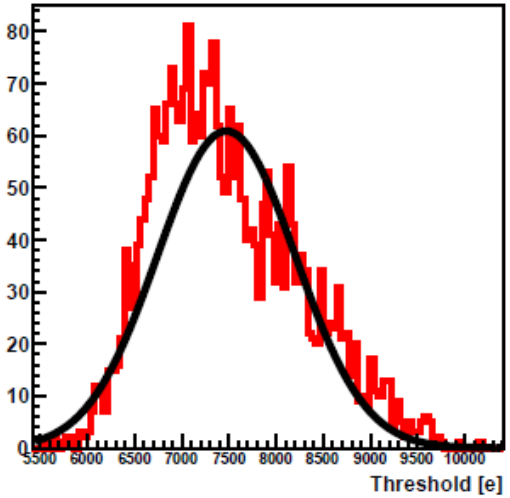


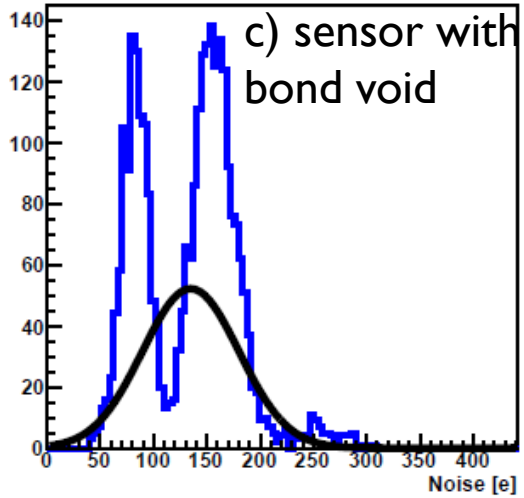
Conversion from the test pulse size to the number of electrons done assuming 3.5fF injection capacitors. Absolute calibration underway.

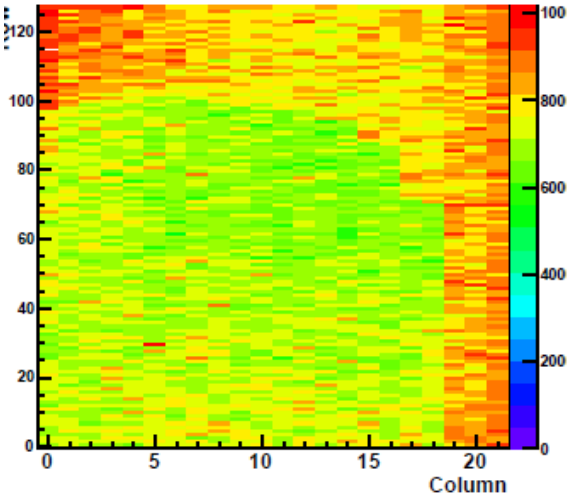
a) with pinning layer C=0.155 pF

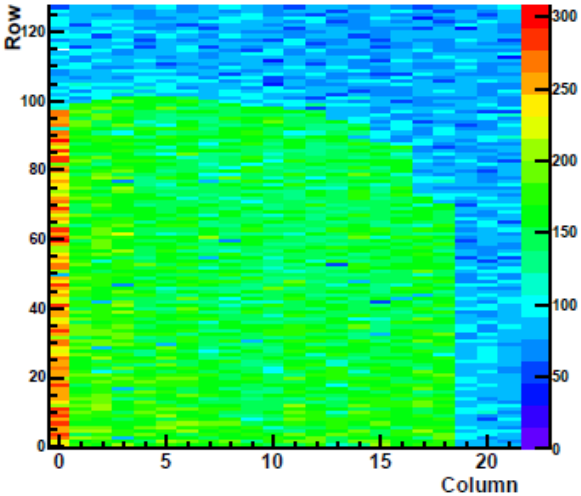
b) w/o pinning layer C=0.106 pF

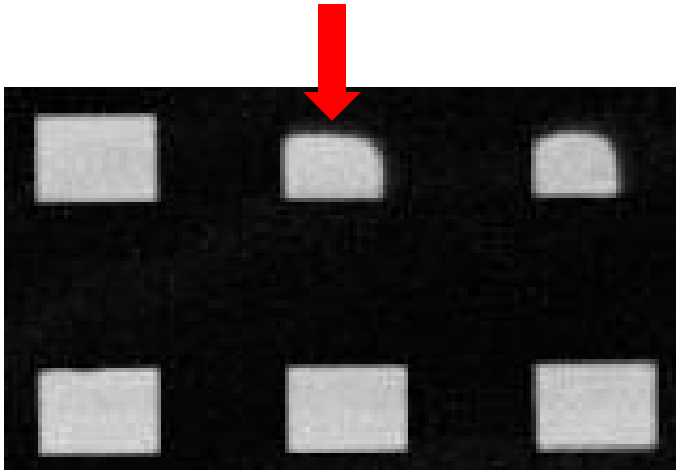
Threshold Scan – Sensor with Bond Void





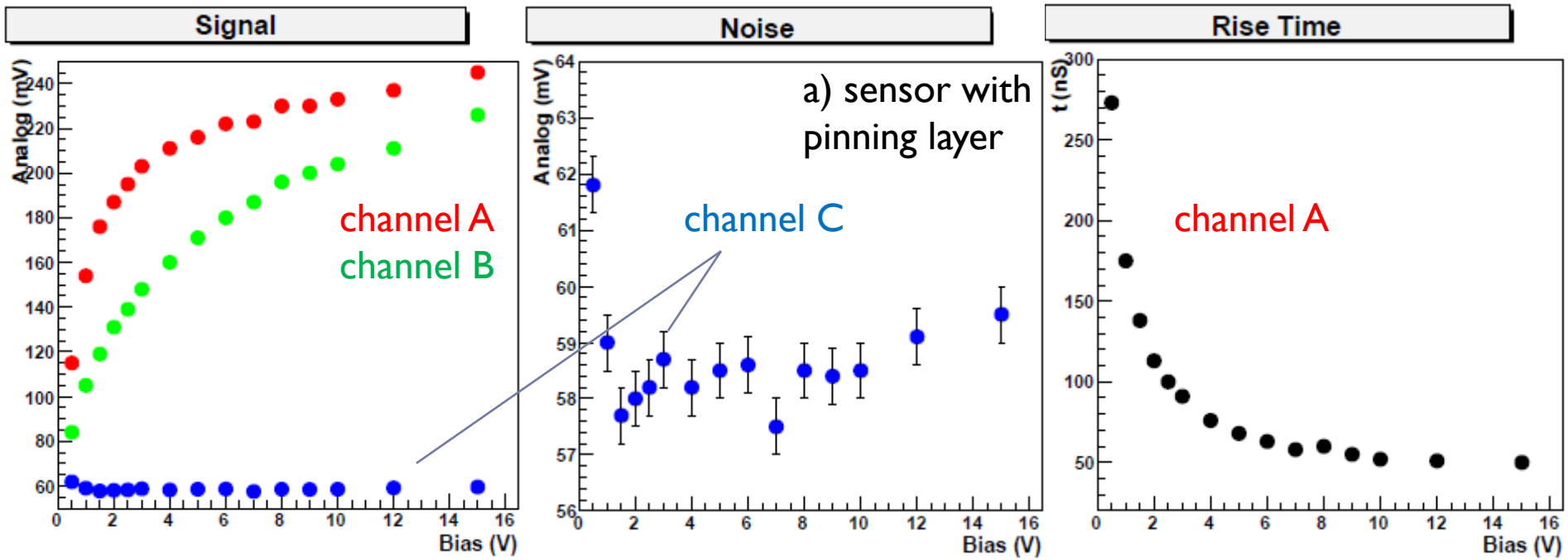






Scanning Acoustic Microscopy

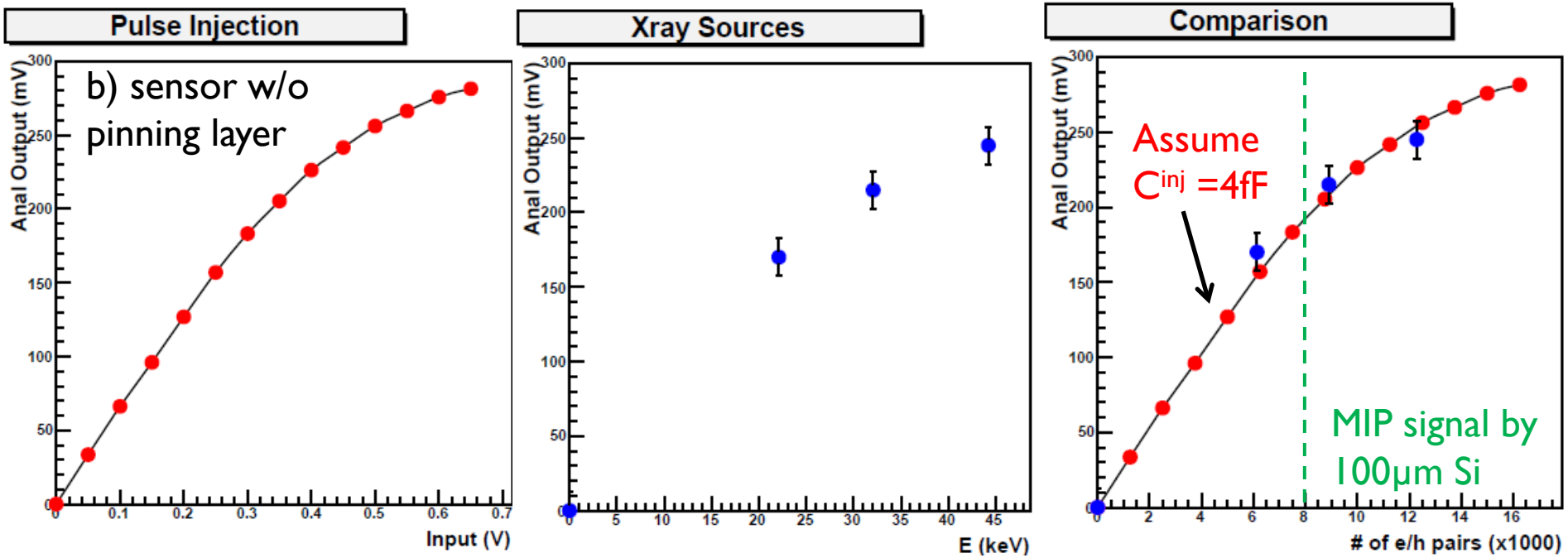
Analog Outputs Due to Laser (E=1.13eV)



Inject a laser onto the sensor backside. Measure the analog outputs of two FPIX channels (A, B) close to the laser, and that of a channel (C) far way from the laser.

- ❑ Amplitude of Anal_Out of A and B increase versus bias – depletion volume increase.
- ❑ Amplitude of Anal_Out of C (interpreted as noise) decreases versus bias – input capacitance of the sensor to the FPIX pre-amplifiler decreases versus bias.
- ❑ Rise time of A decreases versus bias – drifting starts to dominate over diffusion.

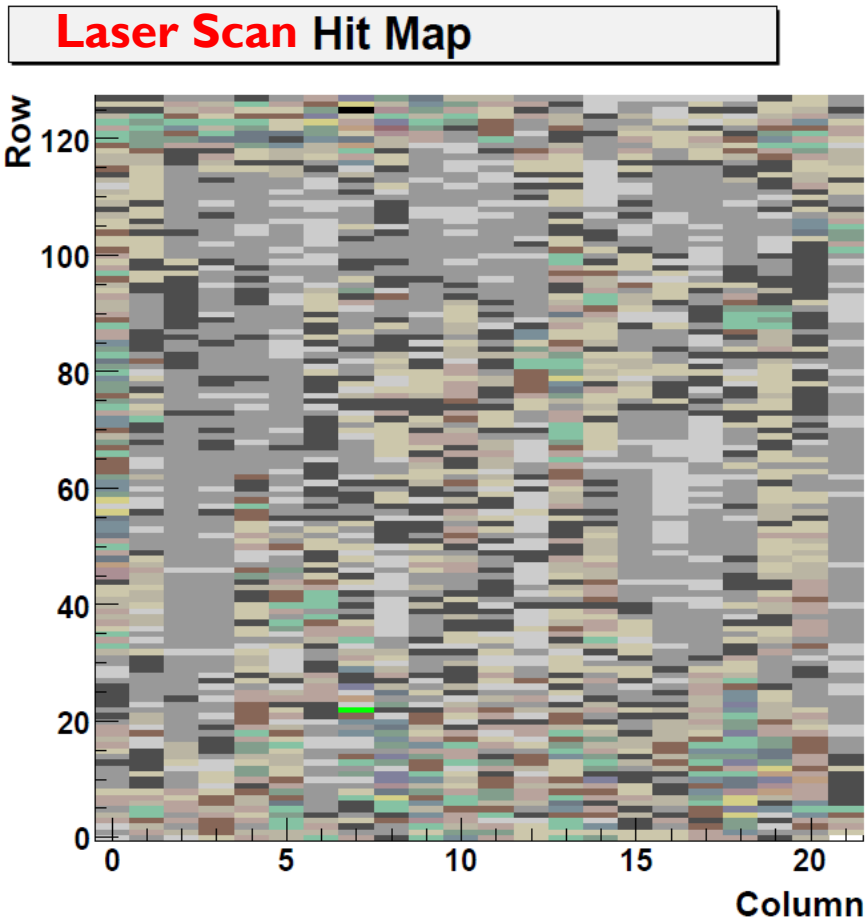
Absolute Calibration Using X-ray Sources

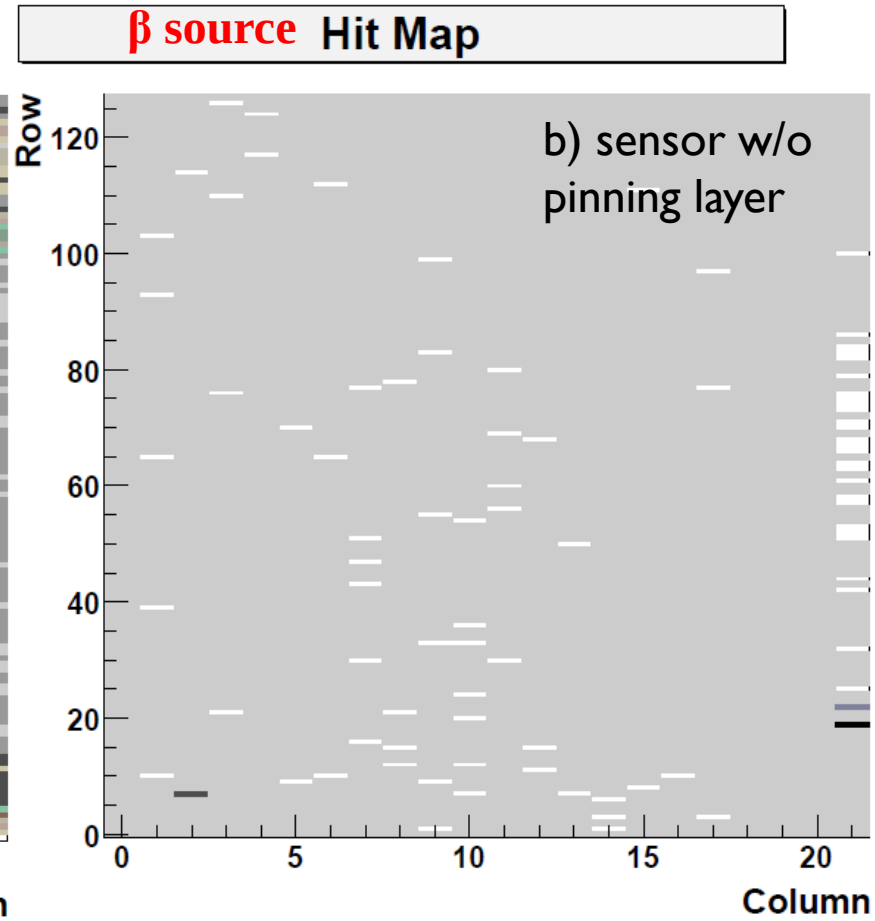


Use a variable X-ray source (metal films in front of Am-241) for absolute calibration:

- ❑measure the (analog output) response curve by charge injection;
- ❑measure (analog output) response to X-ray with different energies (22/32/44 keV);
- ❑converting both of them to # of e/h pairs (to constrain injection capacitance C^{inj}).

Digital Outputs Due to Laser and β Source

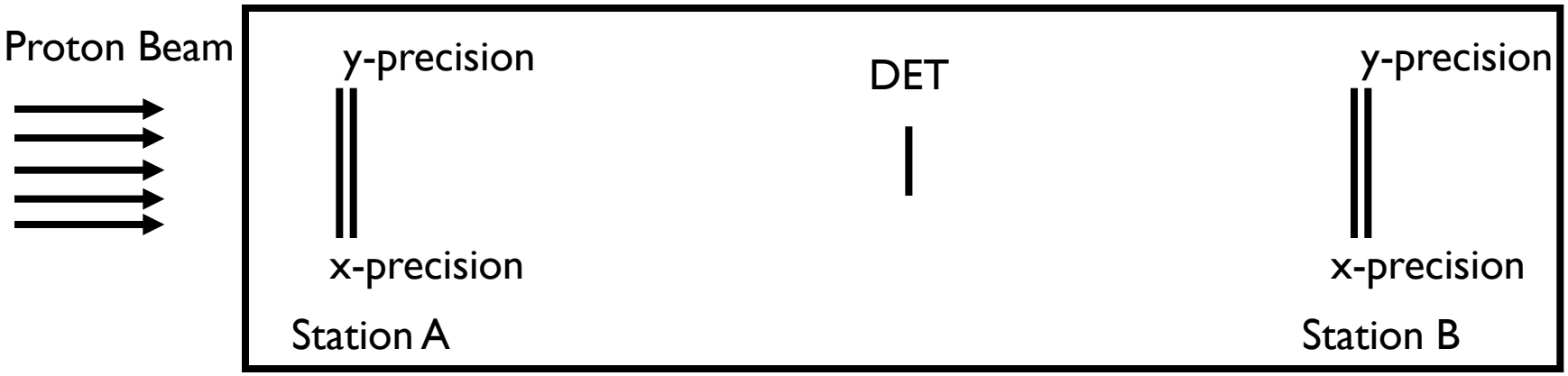




We are able to see the digital outputs of most of the channels due to the laser and due to a β source (Sr-90).

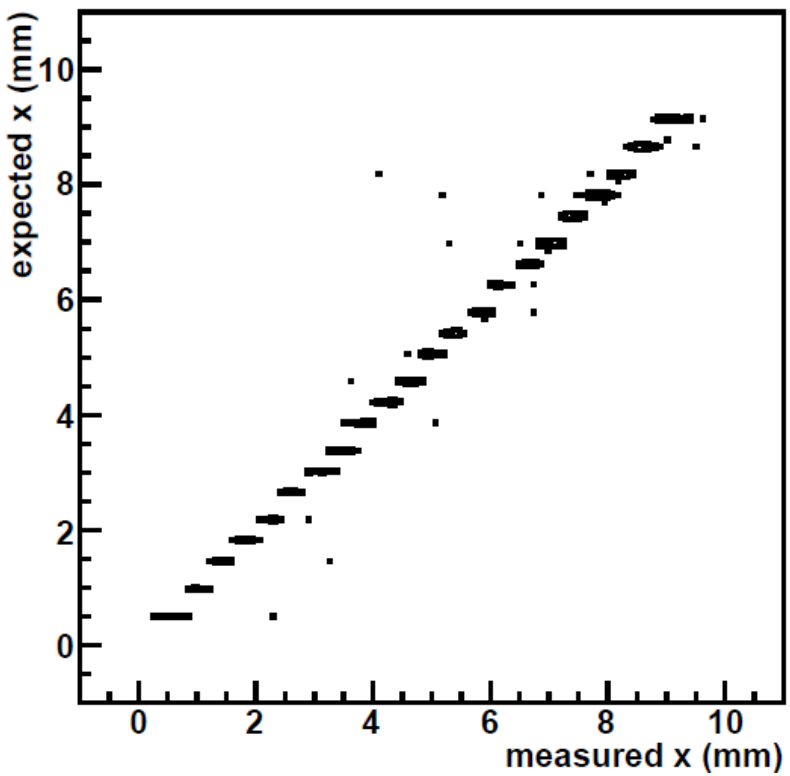
Test Beam Tests

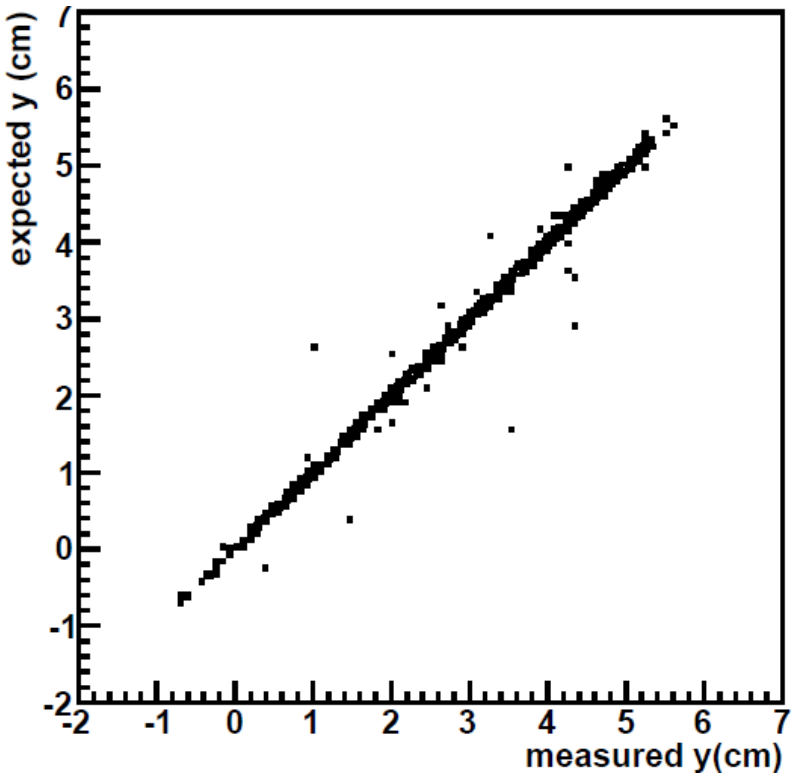
- Fermilab Meson Test Beam Facility 120 GeV proton beam perpendicular to the telescope and DET.
- Two telescope stations of BTeV pixel sensors, with one bit of digital output ("hit") from each 50x400μm pixel unit.



- X/Y positions of the reconstructed hits are "semi-discrete".

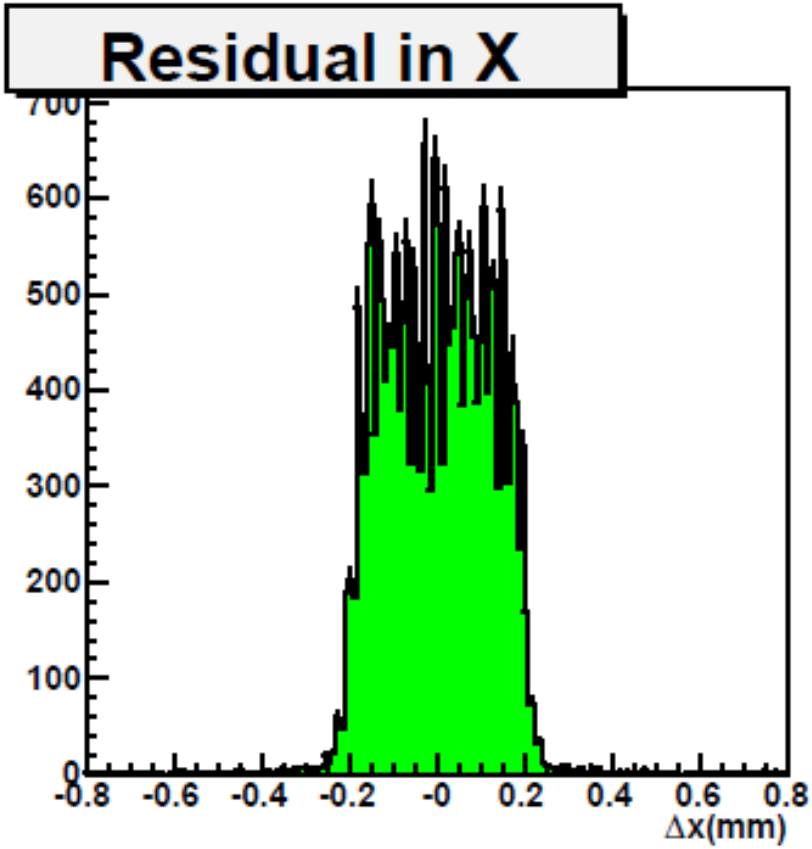
Test Beam Test

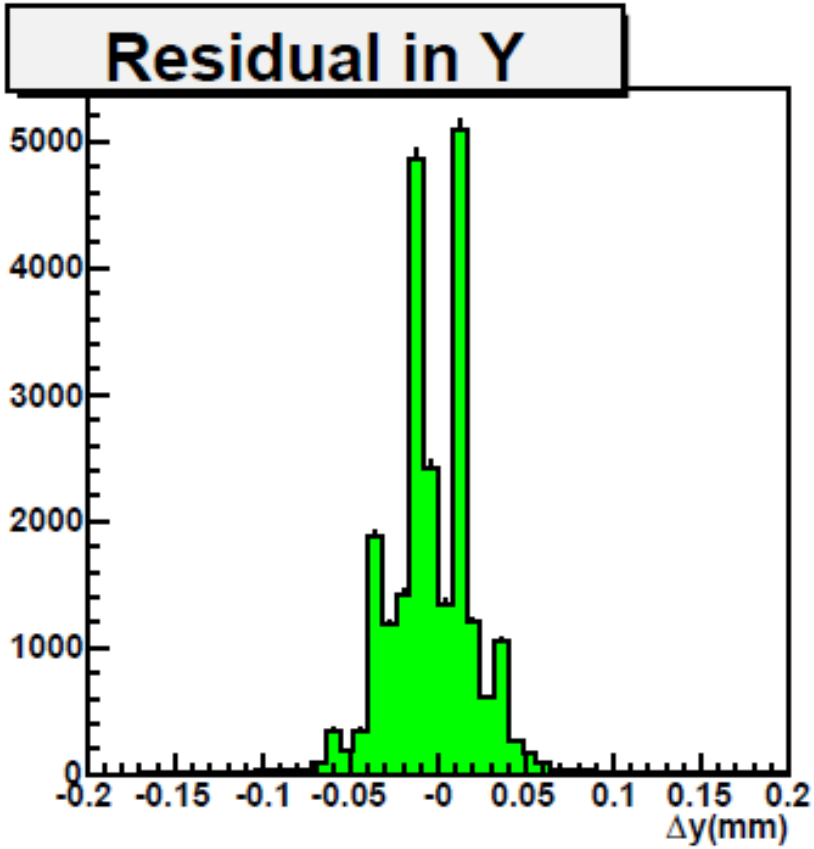




Test Beam Test

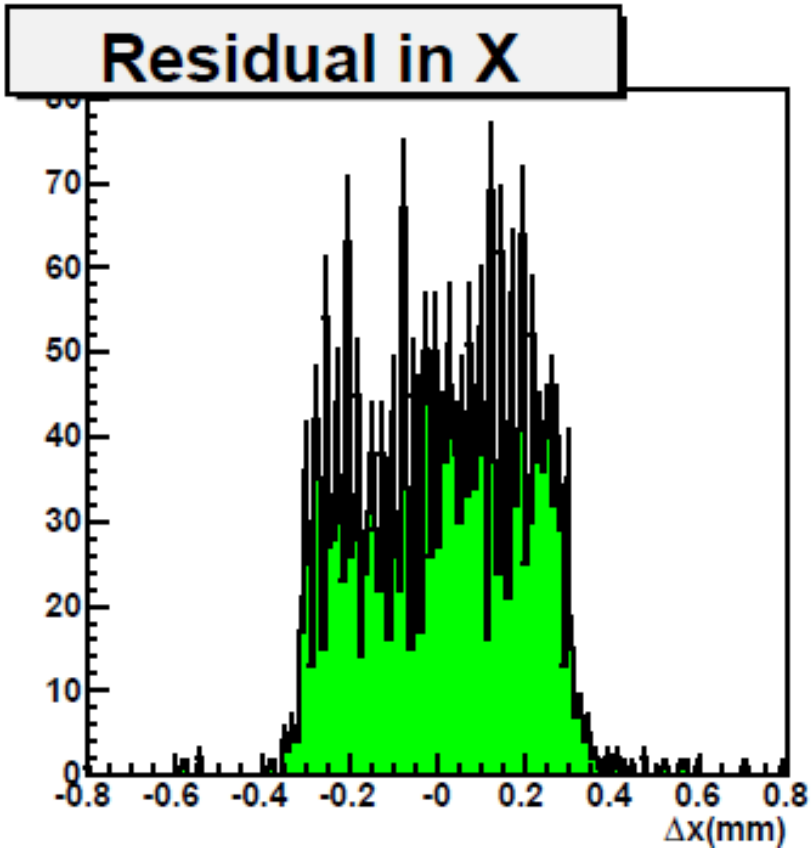
Column 2nd-21st : 400 x 50 μm

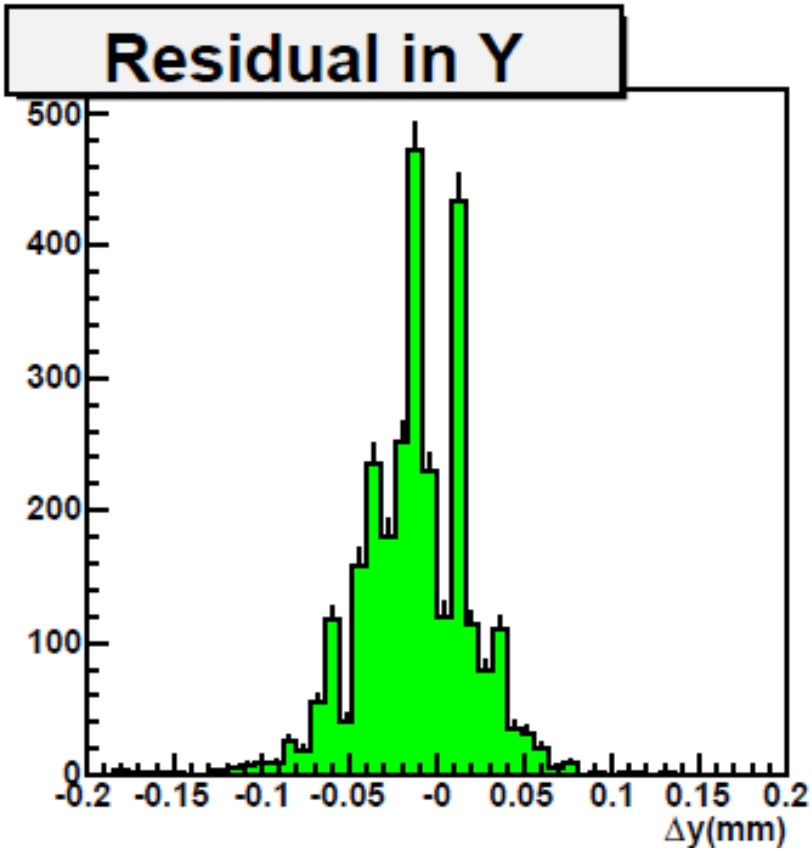




Test Beam Test

Column 1st and 22nd : 600 x 50 μm





Summary and Outlook

- The DBI technology as a replacement of bump-bonding for particle physics pixel sensor/ROIC integration:
  - Low mass, fine pitch;
  - Sensor/ROIC thinning possible after bonding;
  - Available commercially, fairly inexpensive.
- First tests of DBI bonded devices promising:
  - Edgeless trench pixel sensor mated to FPIX2.1 chip;
  - A very small number of interconnect failures;
  - Sensor input capacitances seem to be small.
- To-do
  - Radiation damage for DBI bonding, planned in Nov, 2009
  - Charge collection near/outside the trench in test beam for the edgeless sensor.

Backup Slides Start Here

Edgeless Trenched Pixel Sensor

- p+ diodes on n bulk (ρ=5kΩ·cm)
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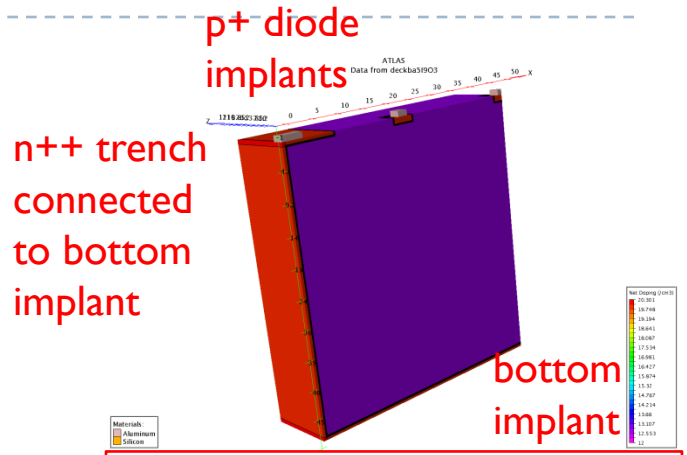
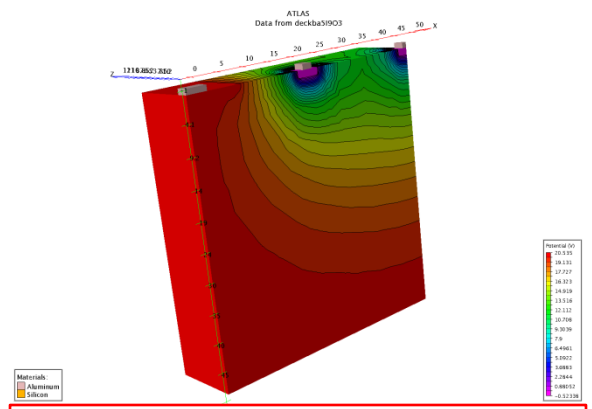


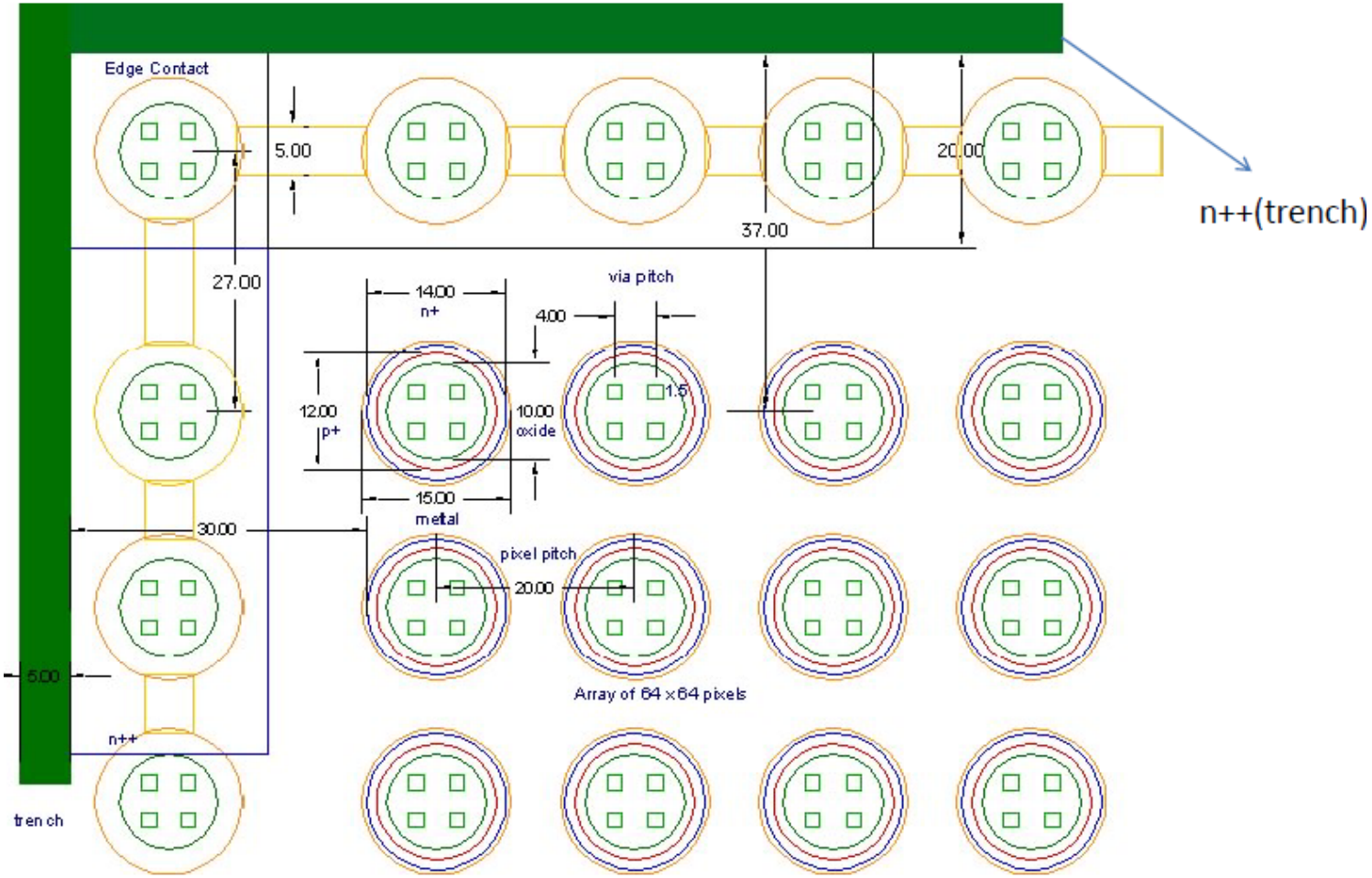
cross section near the edge



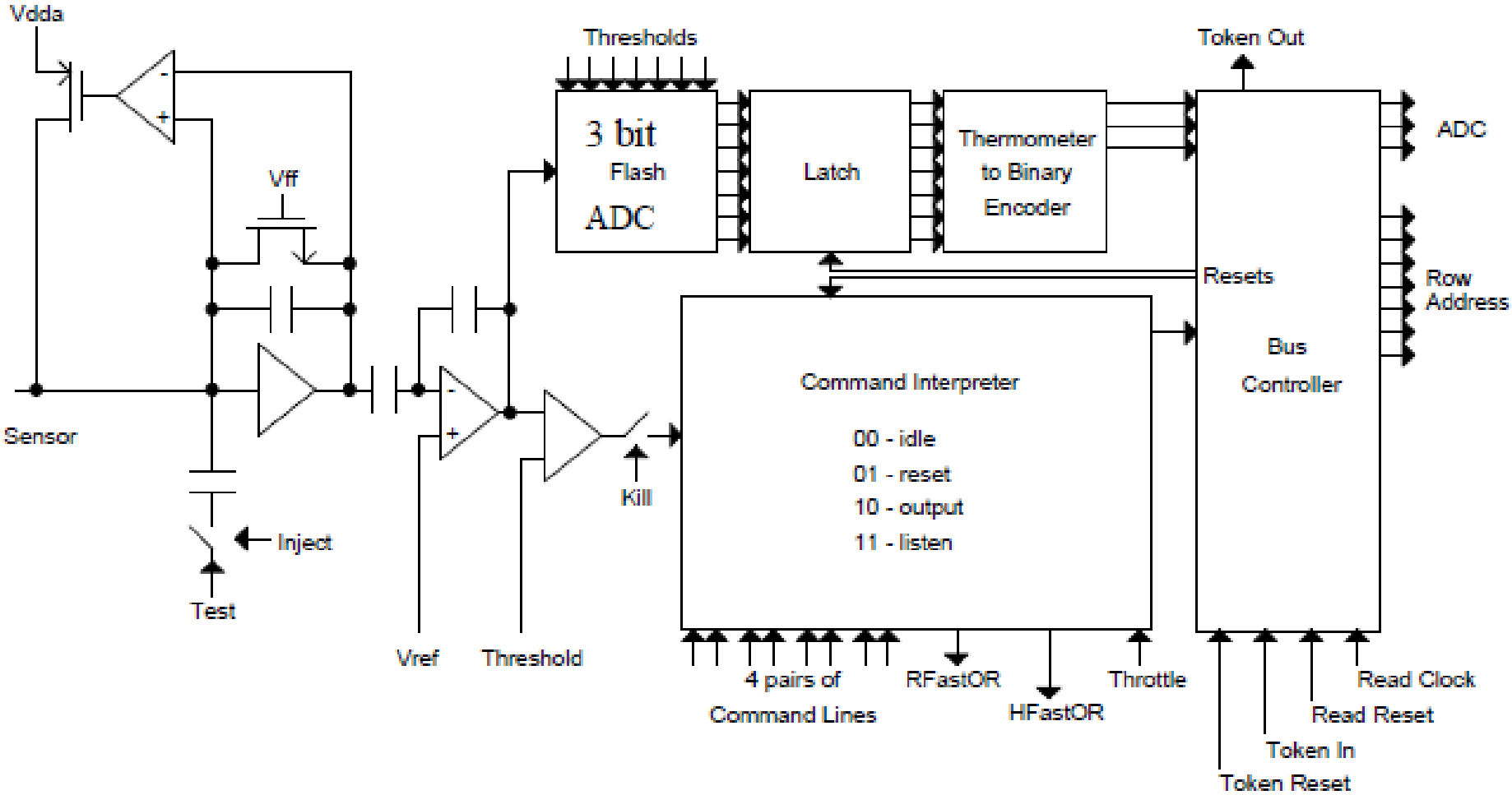
equipotential field lines

Edgeless Trenched Pixel Sensor

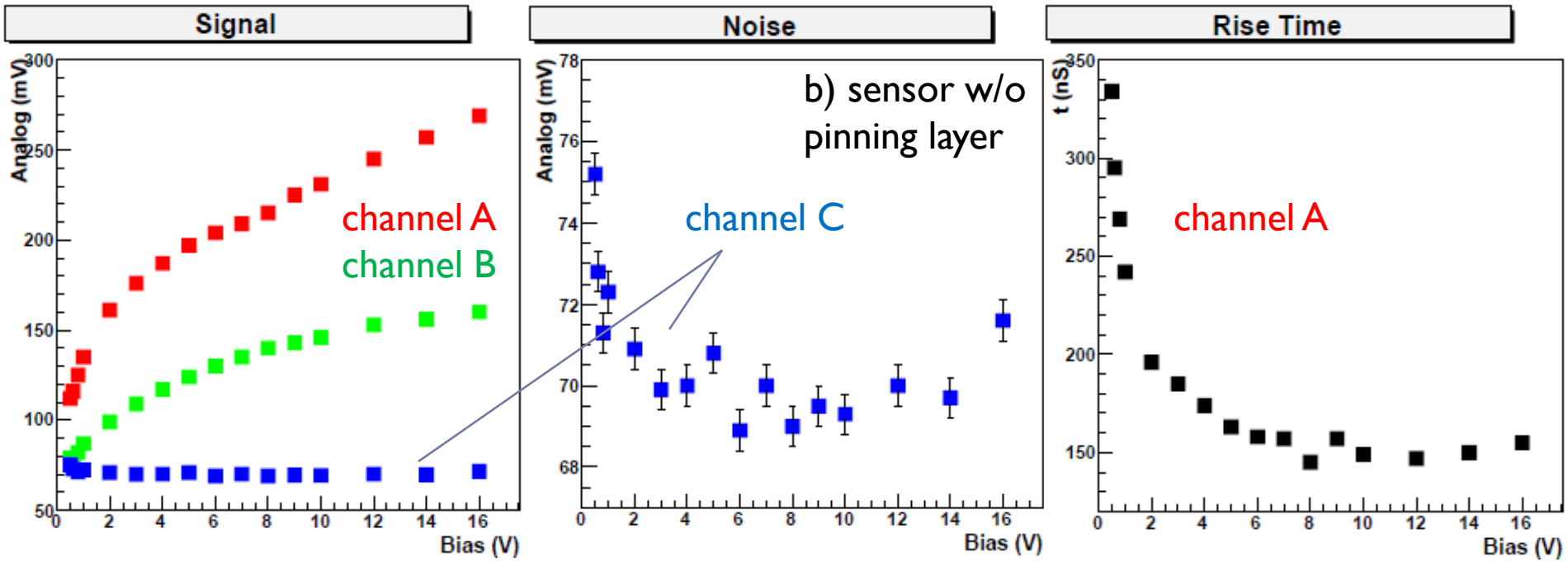
Top view of the pixel array. (20-micron pitch)



BTeV FPIX2.1 Readout Chips



Analog Outputs Due to Laser (E=1.13eV)



Spot a laser on the sensor backside. Measure the analog outputs of two FPIX channels (A, B) close to the laser, and that of a channel (C) far way from the laser.

- ❑ Amplitude of Anal_Out of A and B increase versus bias – depletion volume increase
- ❑ Amplitude of Anal_Out of C (interpreted as noise) decreases versus bias – input capacitance of the sensor to the FPIX pre-amplifiler decreases versus bias
- ❑ Rise time of A and B decrease versus bias – drifting starts to dominate over diffusion