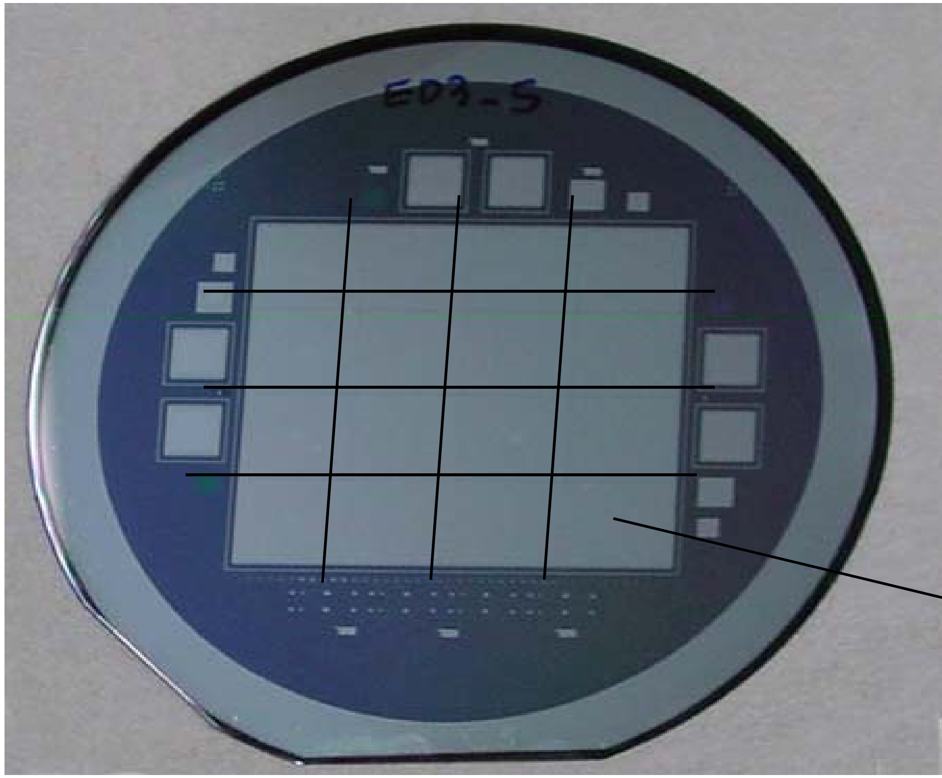
Production of a large number of silicon pixel sensors and the application in comic ray experiment and imaging calorimeter

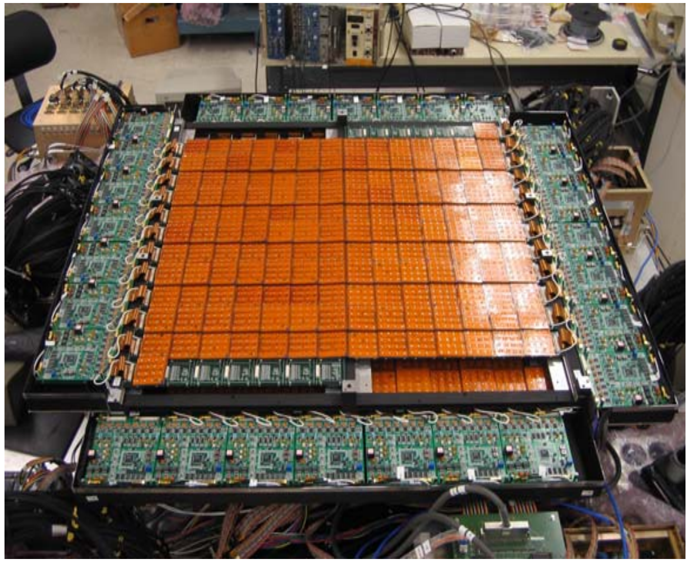


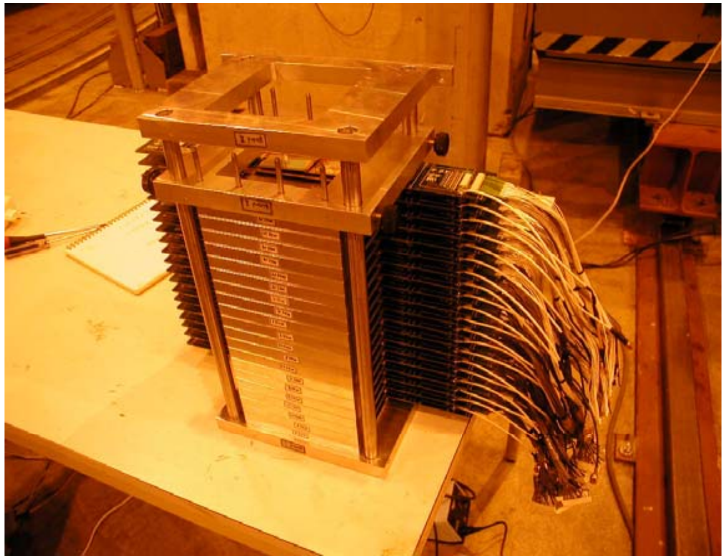
$15*13\ mm^2$

Shinwoo Nam, Il H. Park, Jae H. Park, Nahee Park
(Ewha Univ., Seoul)

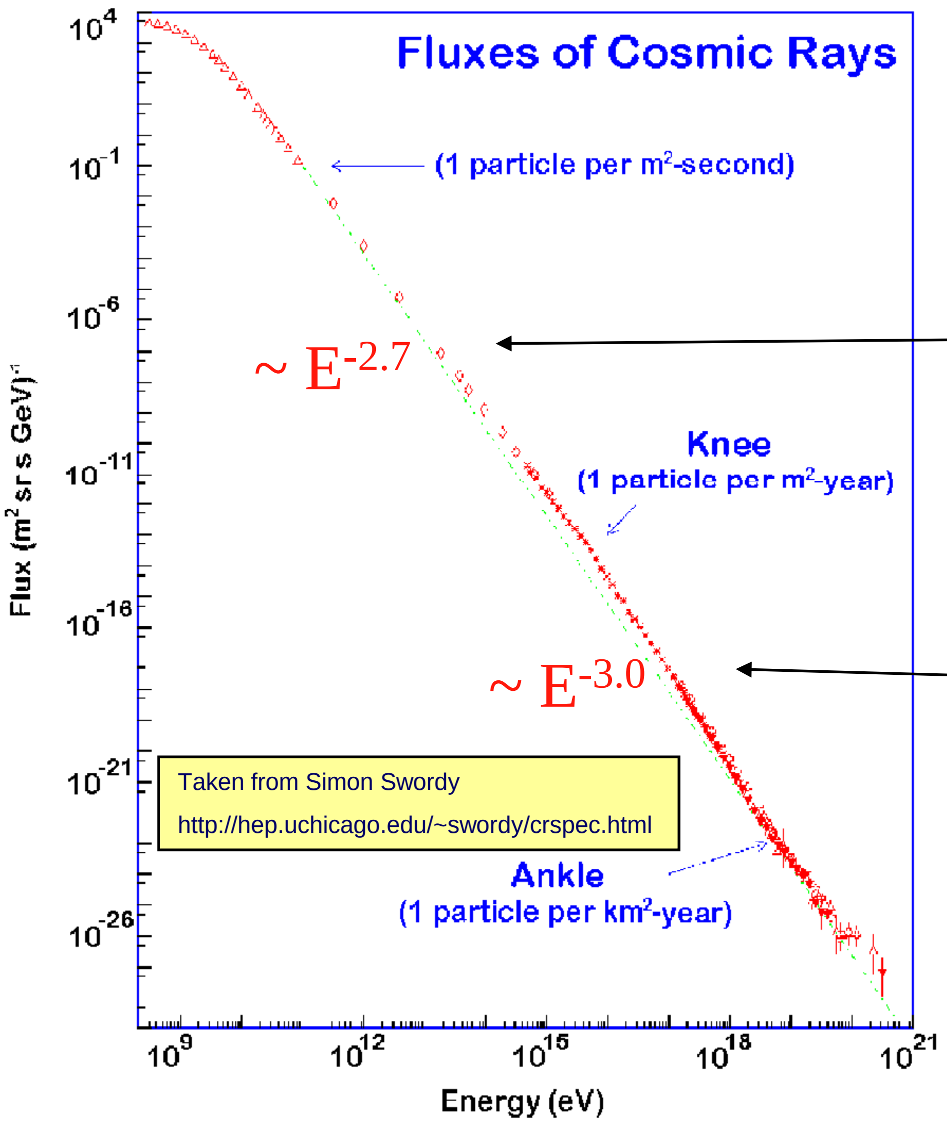
Two Applications

- Cosmic Ray nuclei charge measurement by dE/dx
  - For CREAM Experiment
- Silicon Tungsten Calorimeter
  - For future ILC ECAL and Phenix NCC





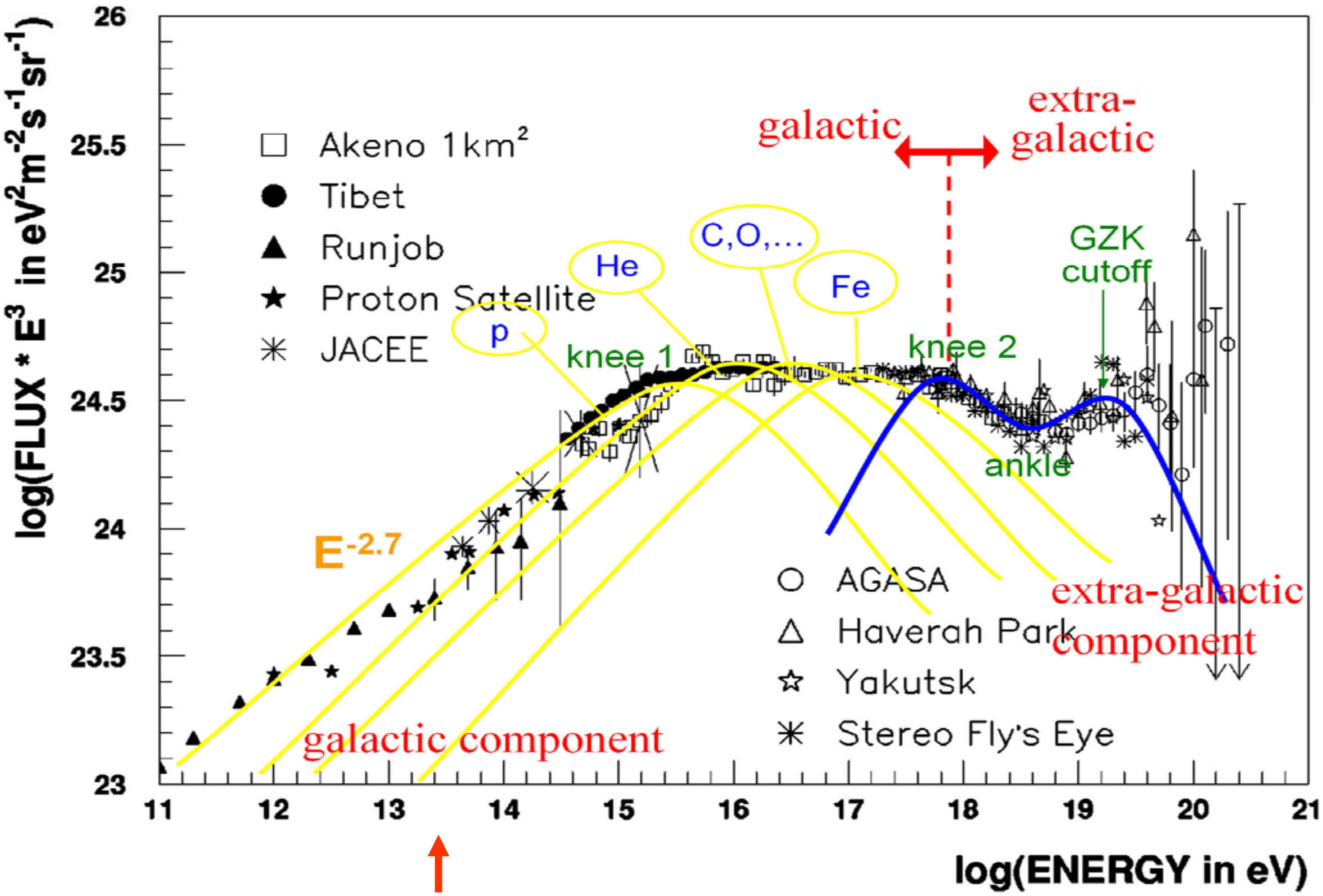
Cosmic Rays



All particle spectrum from direct and indirect cosmic ray observations

Direct Measurement, Balloon, Satellite ($< 10^{15}$ eV)

Indirect Measurement, Air Shower ($> 10^{15}$ eV)



- Galactic component : Stochastic collision with moving magnetic clouds produced from Supernova Remnants accelerates comic rays.
- Acceleration limit increases for high-Z nuclei.

Charge Measurement of high energy particles (10^{12} - 10^{15} eV)

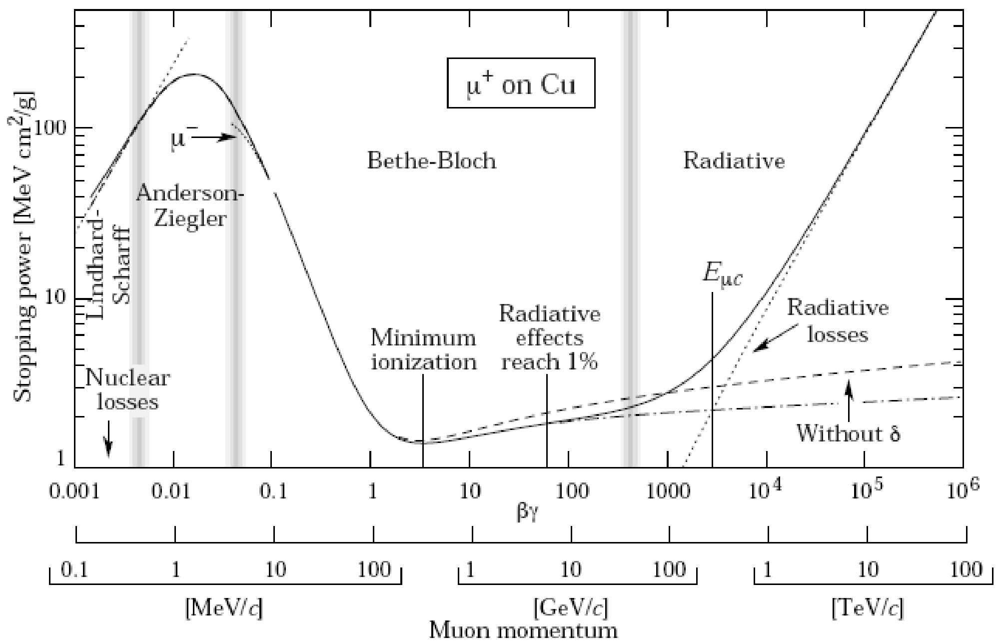
- Energy loss of a charged particle in the matter by Bethe-Bloch formula

$$-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[\ln\left(\frac{2 m_e \gamma^2 v^2 W_{max}}{I^2} \right) - 2\beta^2 - \delta - 2\frac{C}{Z} \right]$$

with $2\pi N_a r_e^2 m_e c^2 = 0.1535\ \mathrm{MeV cm^2/g}$

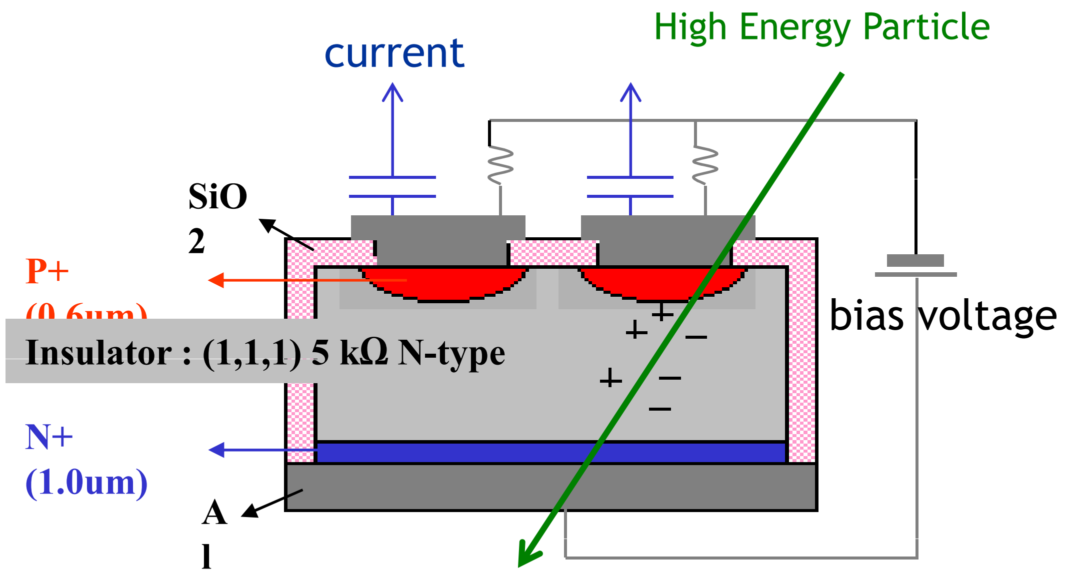
- dE/dx : logarithmic dependence on particle energy
- Radiative energy loss is small for proton and heavy nuclei

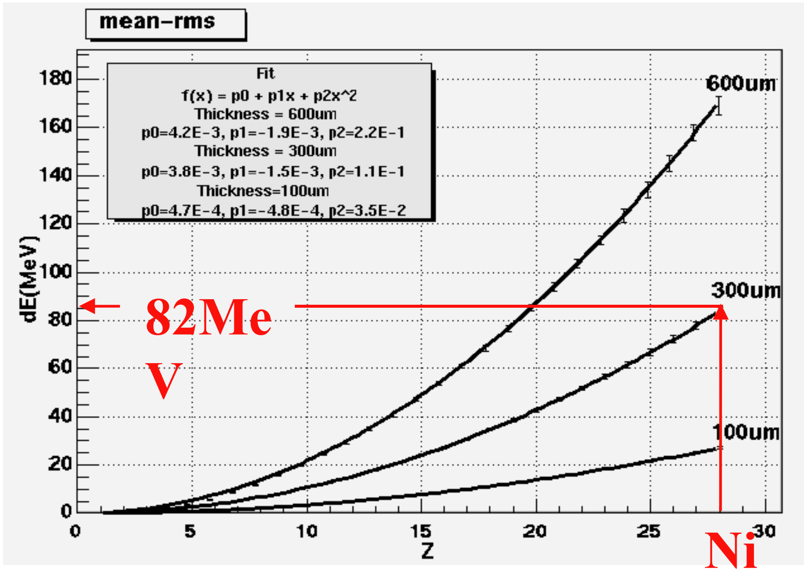
$$\Rightarrow \quad -\frac{dE}{dx} \propto z^2$$



Silicon sensor for charge measurement

- PIN diode operating at full depletion condition
- Produced from wafers of 380 um, 5”, double polished



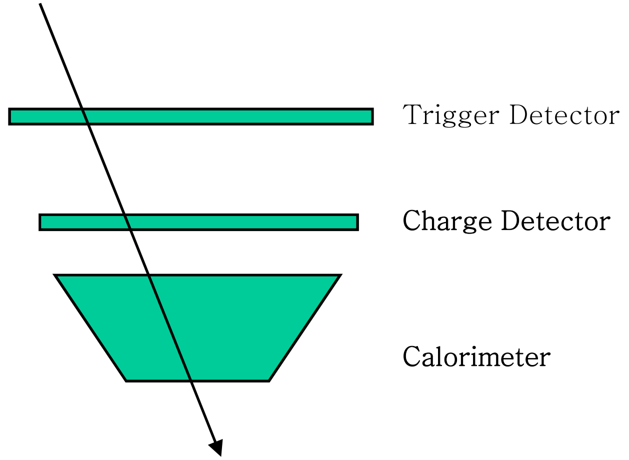


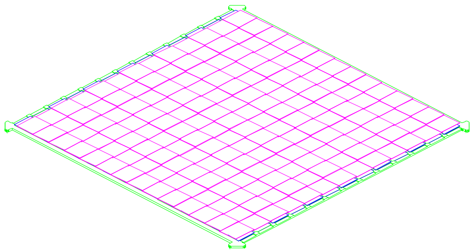
Maximum signal (for 300 um thickness Si)

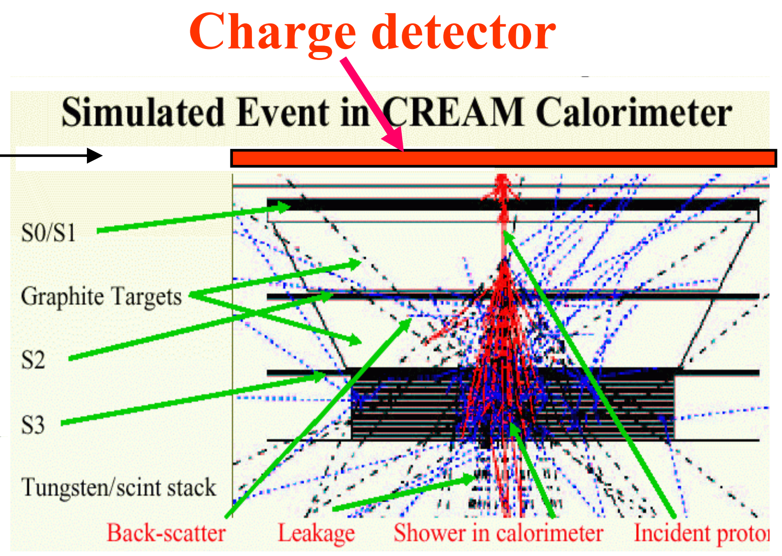
82 MeV / 3.62 eV ~ 2×10^7 holes ~> 3.20 pC

Pixel Size of Sensors

- CREAM is balloon borne experiment to measure cosmic composition in 10^{12} - 10^{15} eV (highest possible energy range for a direct measurement)
- Sensors are installed on top of the calorimeter and target
- Back-scattered particles are produced in the high energy shower
- Pixel size is to be optimized for the performance : 15*14 mm^2 for CREAM





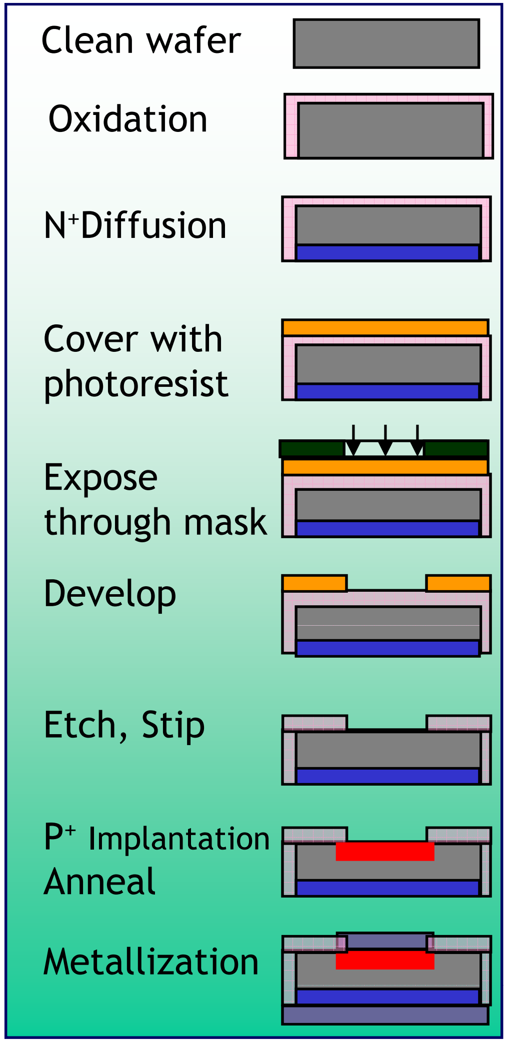


- Area to cover ~ 79 × 79 cm^3
- Number of channel ~ 3000 for a layer -> 180 sensors

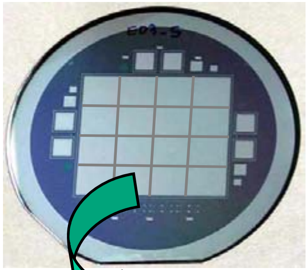
Sensor Fabrication

Fabricated by SENS Technology (www.senstechnology.co.kr)

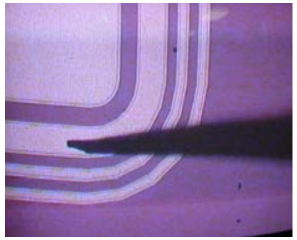
PIN diode structure

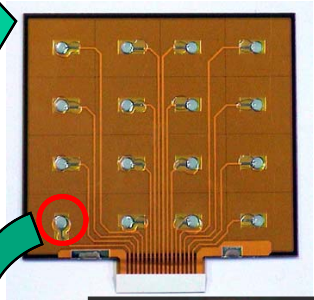


Fabrication process



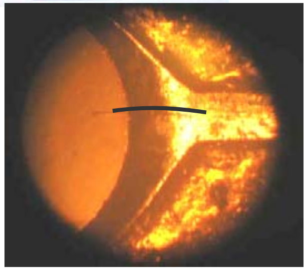
Fabricated sensor
Wafer size : 5 inch
thickness: 380 um
Pixel size : 1.55 $\times$ 1.37 cm^2
Array : 4 $\times$ 4 matrix





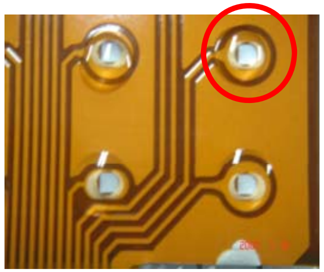
Sawing / attach Kapton tape
for connection to readout

✓Kapton tape
Cu wire with width 50 um



Wire (wedge) bonding
for connection of
Kapton cable to sensor pixel

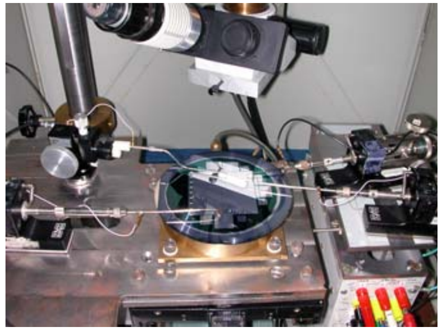
✓Wedge bonding
Al wire with diameter 50 um



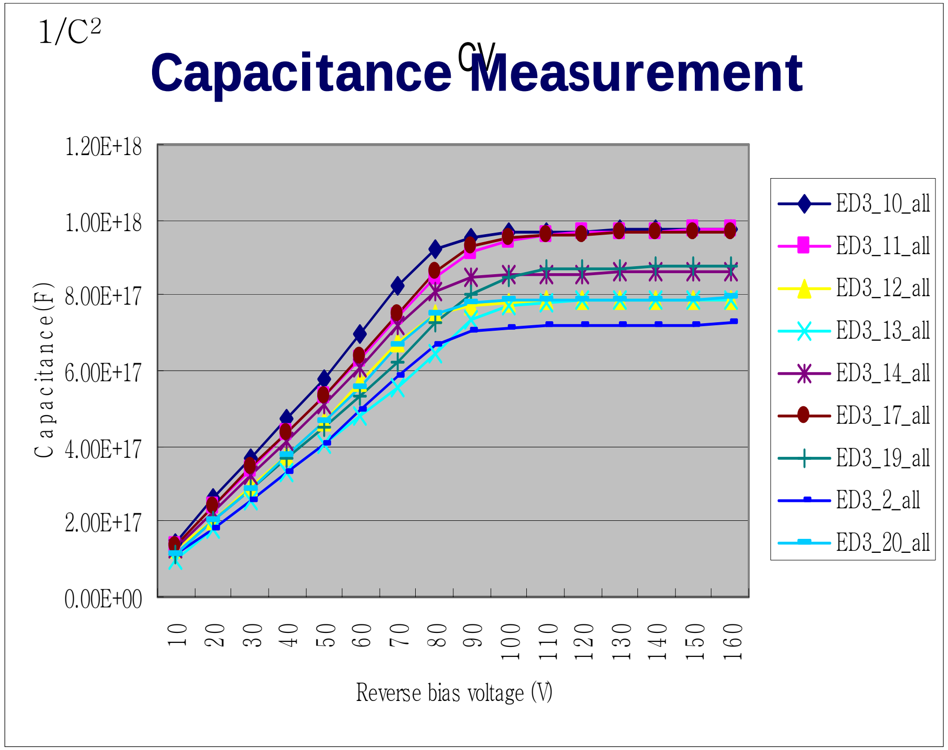
Glob Top
for protection and preservation
of bond wire

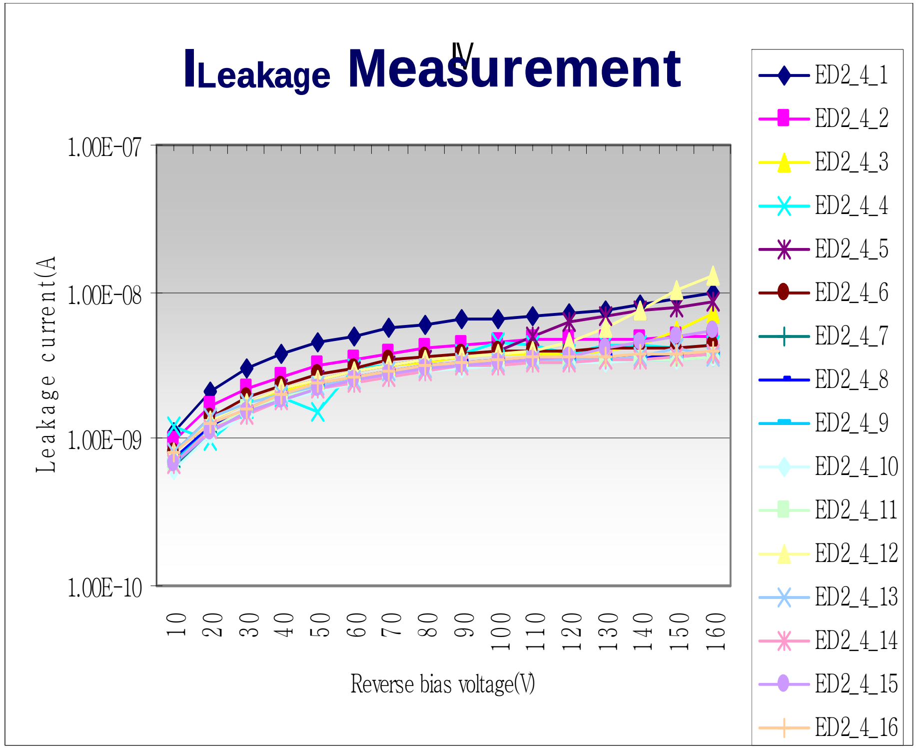
✓Coating
SJC Polychemicals, DCE, DP100

Sensor Performance



~300 sensors for CREAM-1 (2003)
~400 sensors for CREAM-2 (2005)



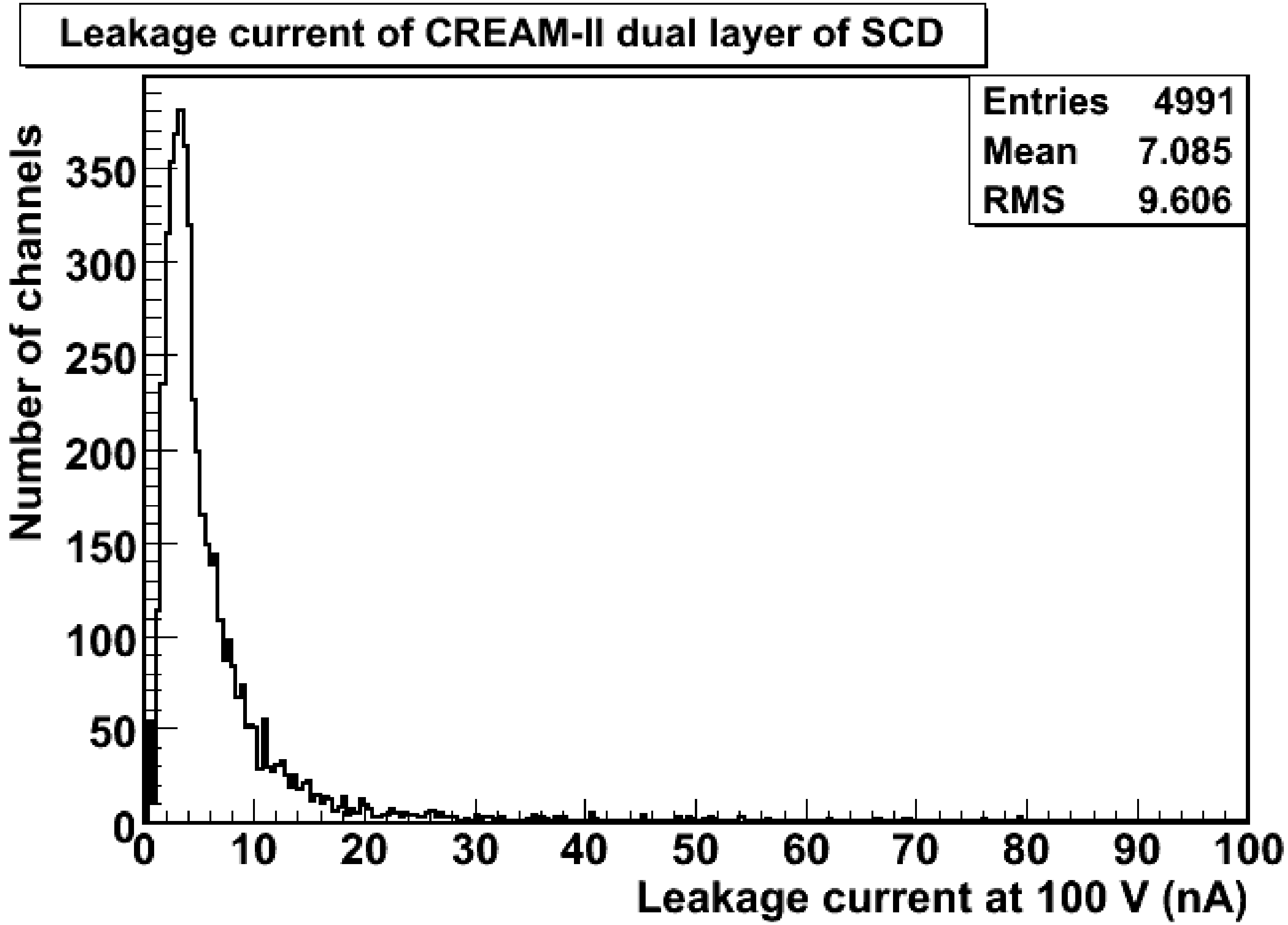


full depletion at ~ 80V
Operation bias at 100V (over depletion) to make sure all sensors are fully depleted.

- **For most sensors leakage current below 10 nA/cm2 at full depletion voltage**

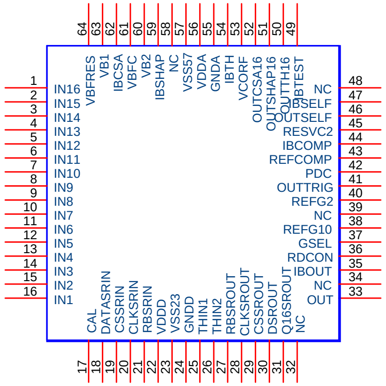
Quality of Sensors

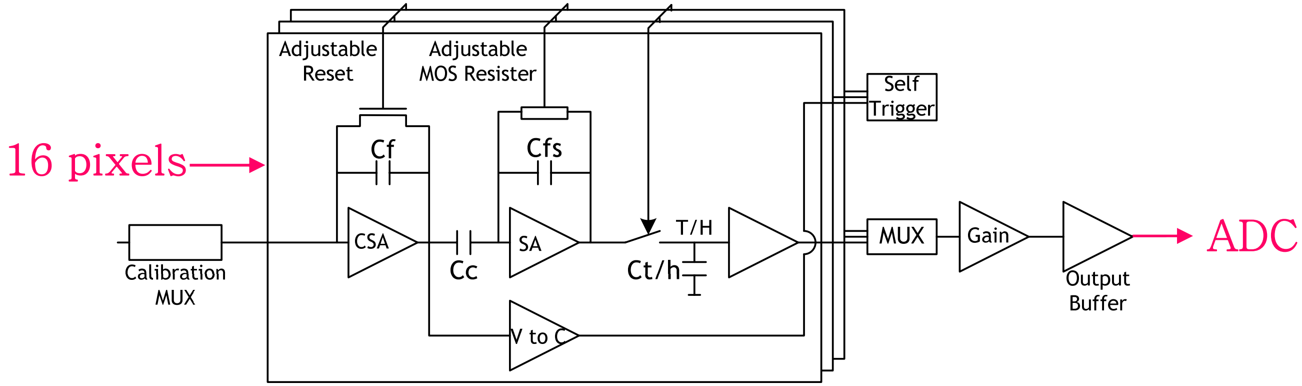
Sensors are biased at 100V (Over-depletion Voltage) to make sure that all sensors are fully depleted with the variation in the thickness and resistivity



Analog Electronics (Frontend Readout)

Frontend readout chip : CR1.4

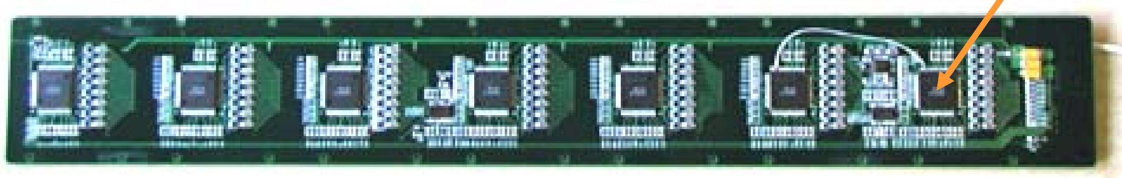


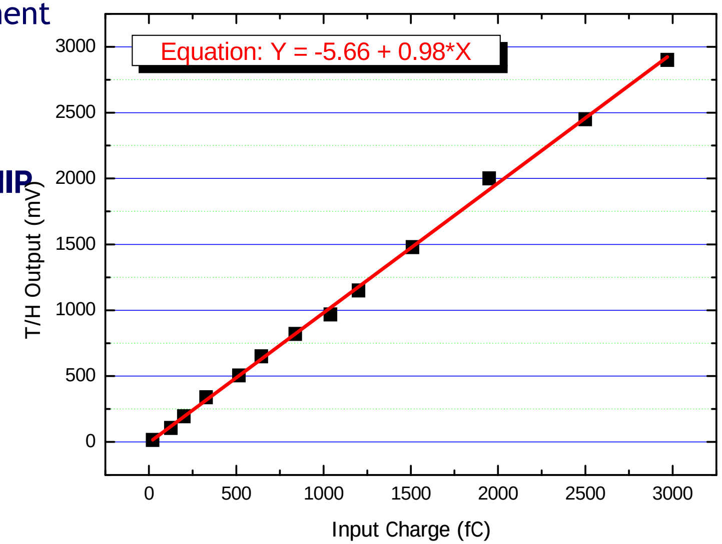


CR1.4 ASIC

- Custom VLSI (Very Large Scale Integrated circuit) chip
- Developed for large arrays of silicon detectors in the Pamela experiment
- 16 channels of charge inputs
  (integrating the charge pulses -> DC levels)
- Multiplexed to common output line
- **Dynamic range : a few fC to about 9 pC with 1 mV/fC Gain, 1200 MIP**
- Power consumption : ≤ 6 mW/channel, ≤ 100 mW/chip
- Noise ~ 5000 e-

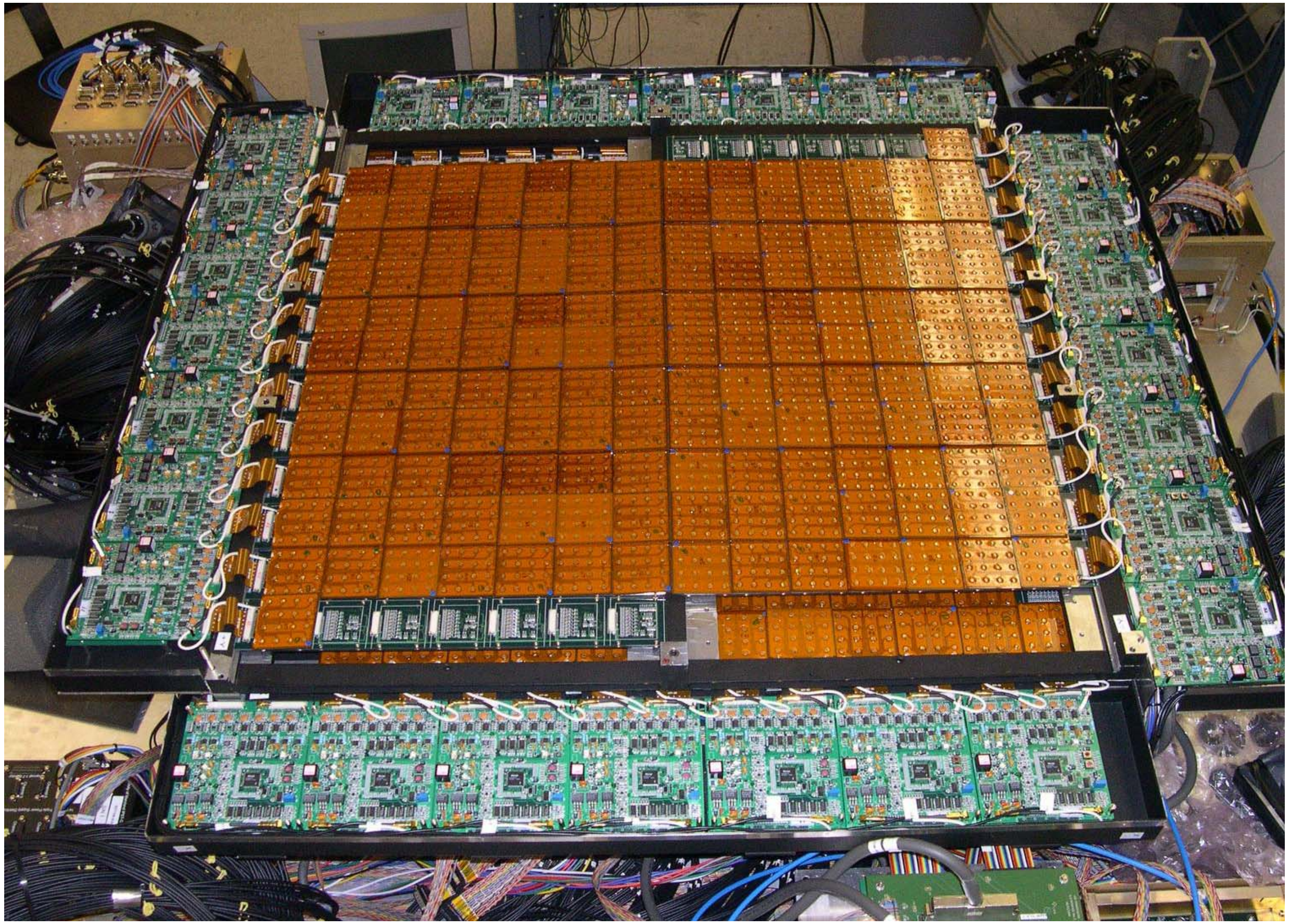
CR1.4





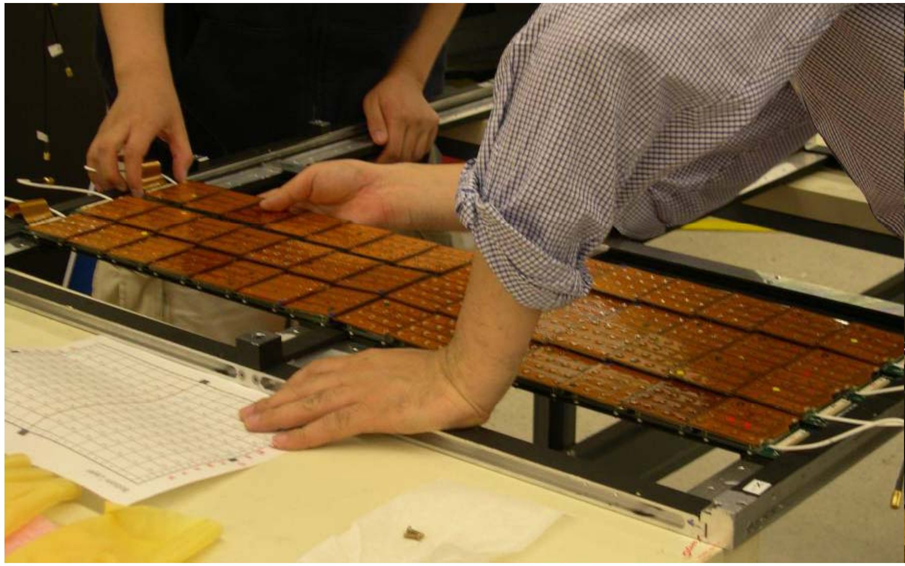
- 1 analog board = 7 CR1.4 * 16 channels = 112 channels

Silicon charge detector used in the second flight (2006.01, 28 days, Antarctica)

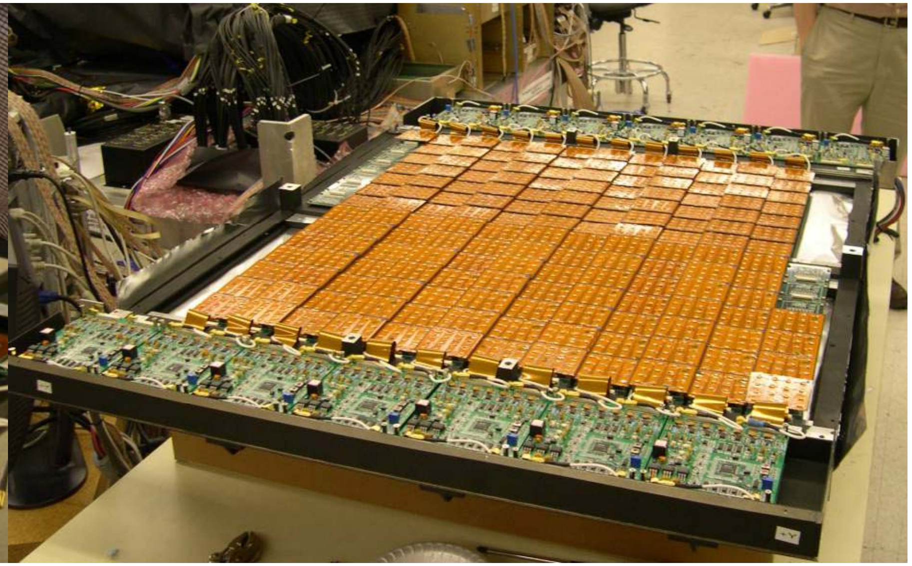


- Total 4864 channels, 304 sensors
- Sensitive area 779*795 cm^2, No dead area between sensors
- Consume power of 136W, Total 56kg, total height 100mm

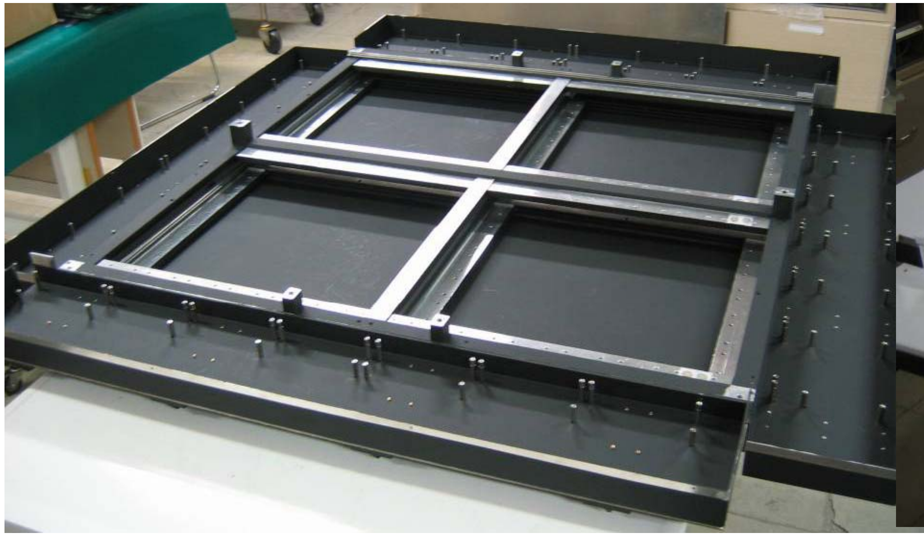
SCD Assembly



Mounting the assembled ladder



Assembled SCD (1 layer)

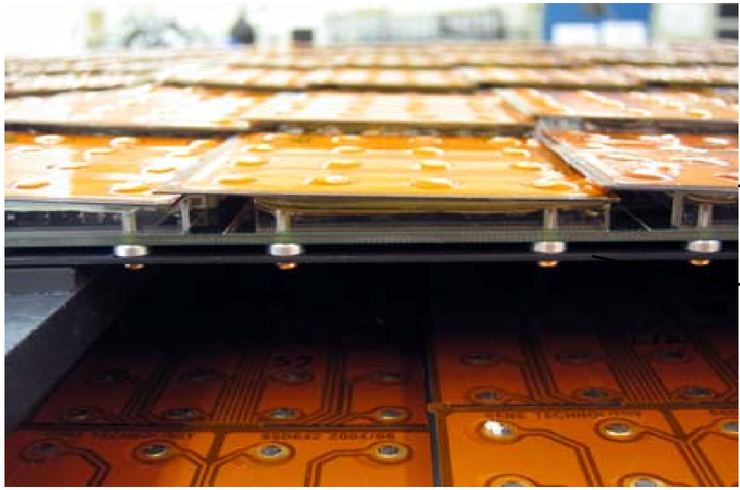


SCD mechanical structure

SCD cover

No damaged sensor was found after 28 days flight and parachute landing

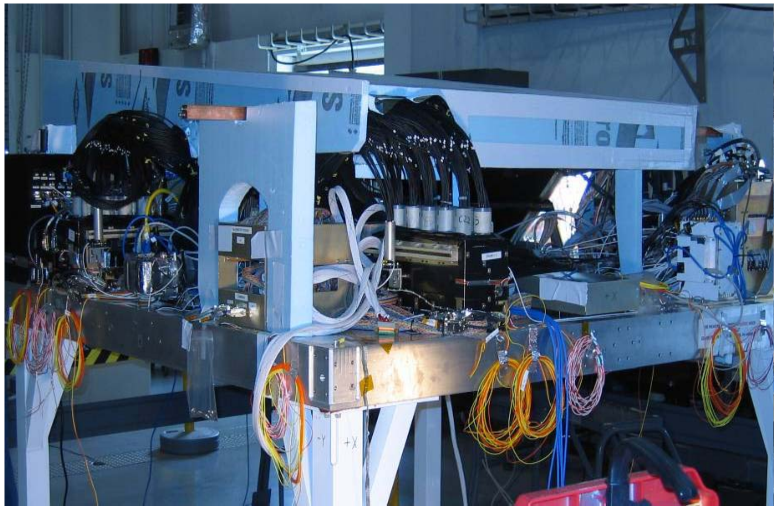
Thermal solution



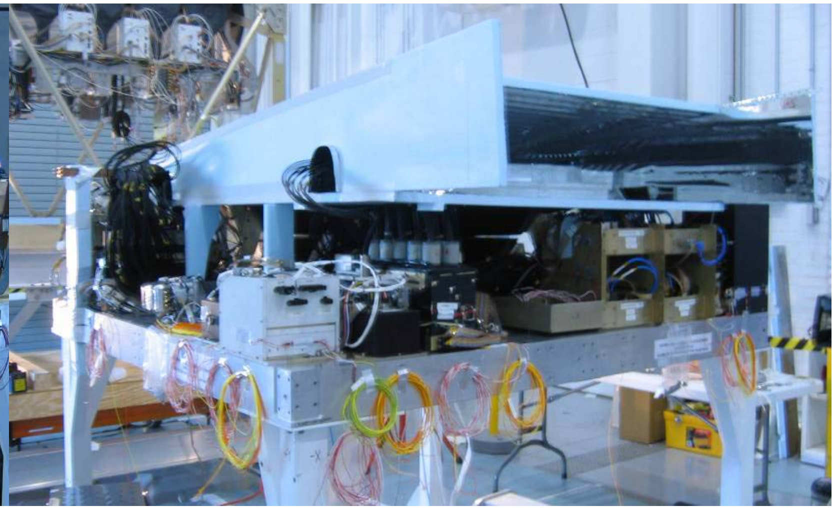
sensors

Analog board

Thermal strap (aluminum 2mm)

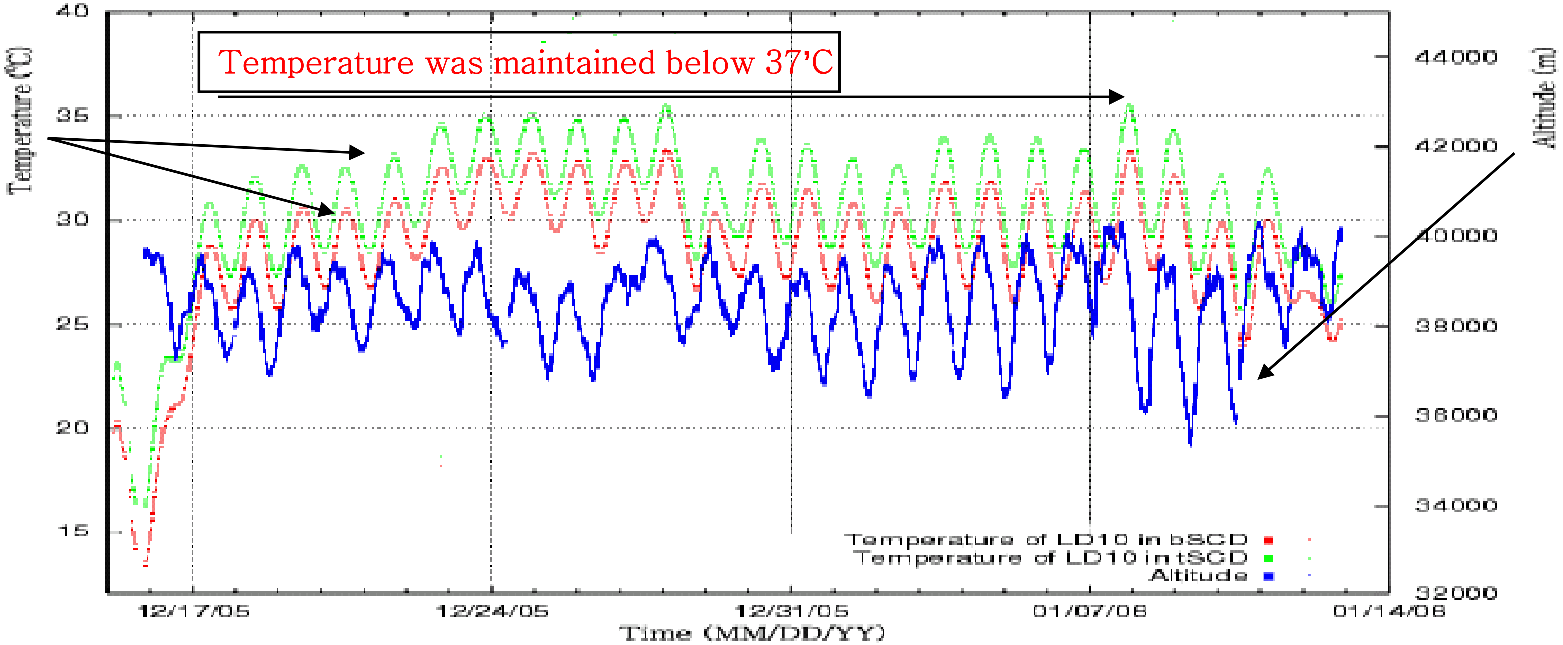


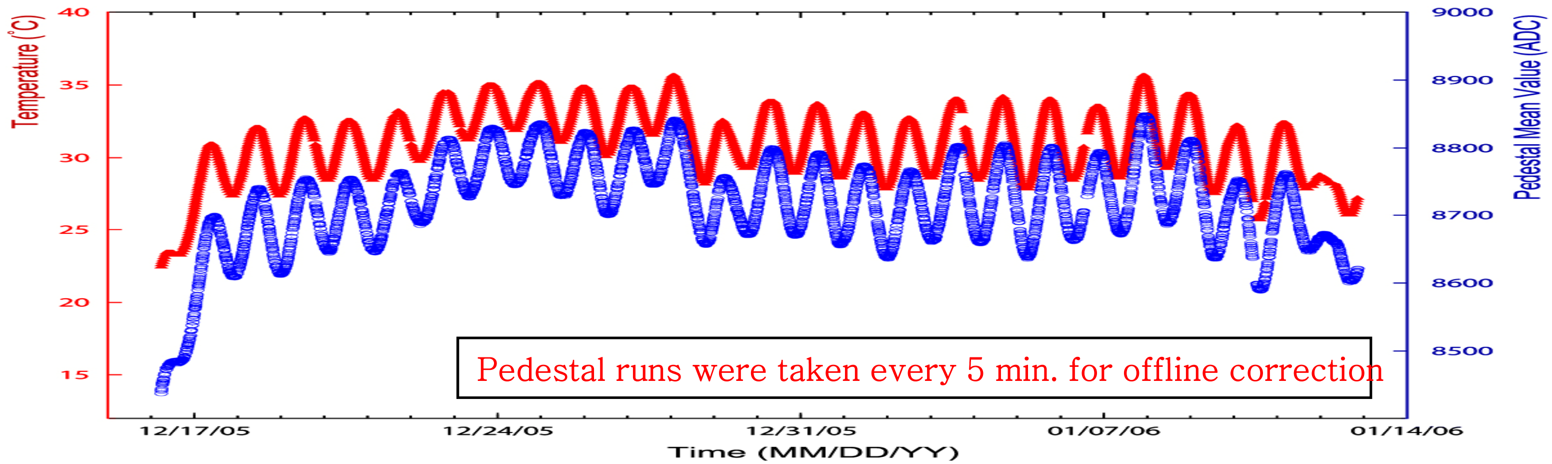
SCD radiator (sun-side)



SCD radiator (anti sun-side)

Flight Monitoring





Channel Performance

95% of channels performed very well to see MIP.
Rest 3.5% are good for high z events analysis.

Top SCD Summary

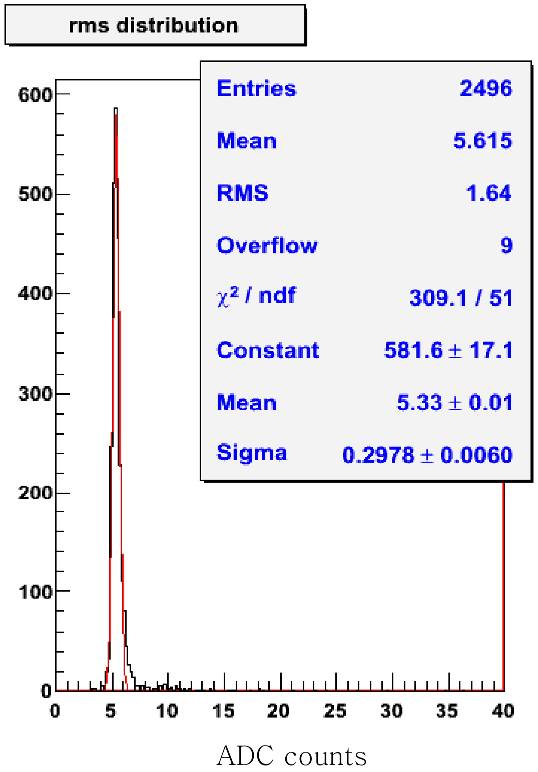
In 2496 effective channel :

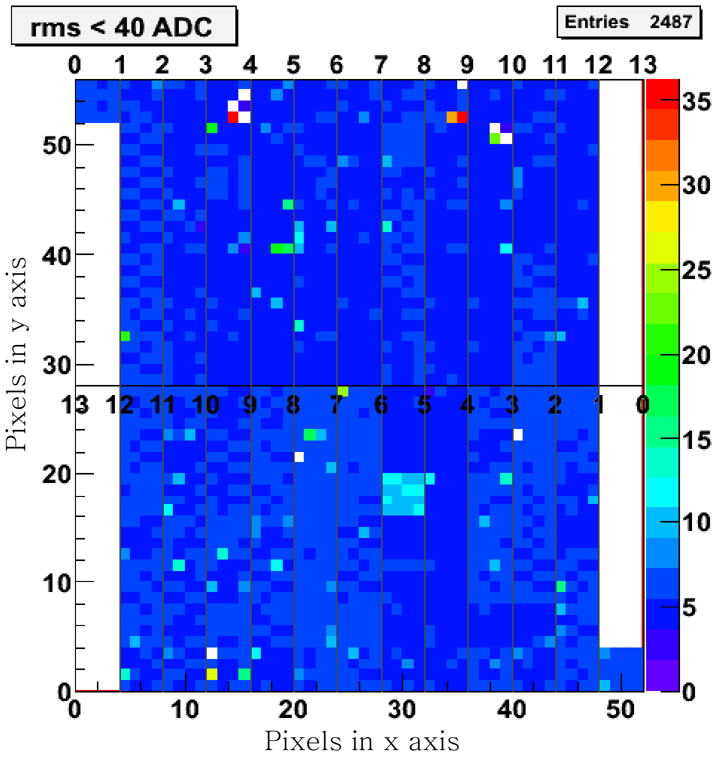
Average pedestal result during the flight

rms≥40: 9 chs, 0.4 % ave rms 102 ADU

10≤rms<40: 45 chs, 1.8 % ave rms 14.8 ADU

rms<10 : 2442 chs, 97.8 % ave rms 5.44 ADU





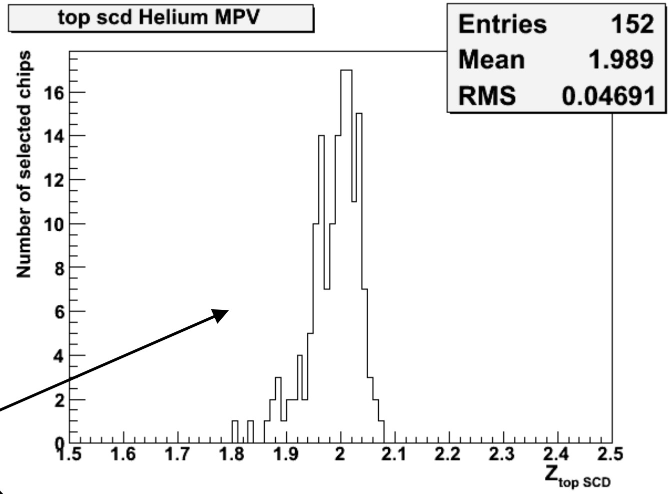
(Proton signal is ~20 Counts above pedestal)

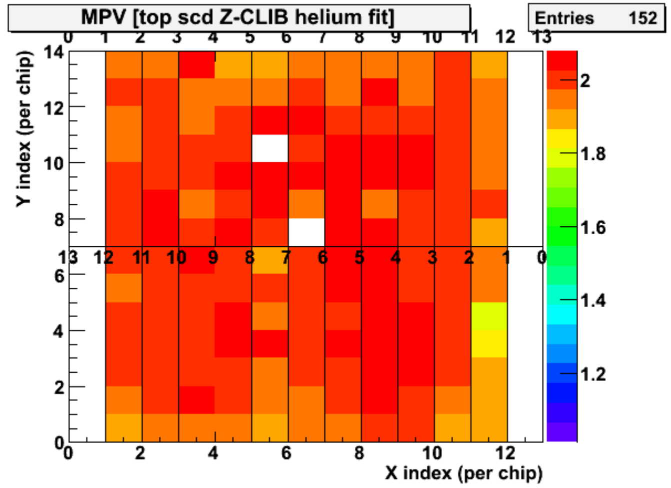
Calibration Data and Channel Uniformity

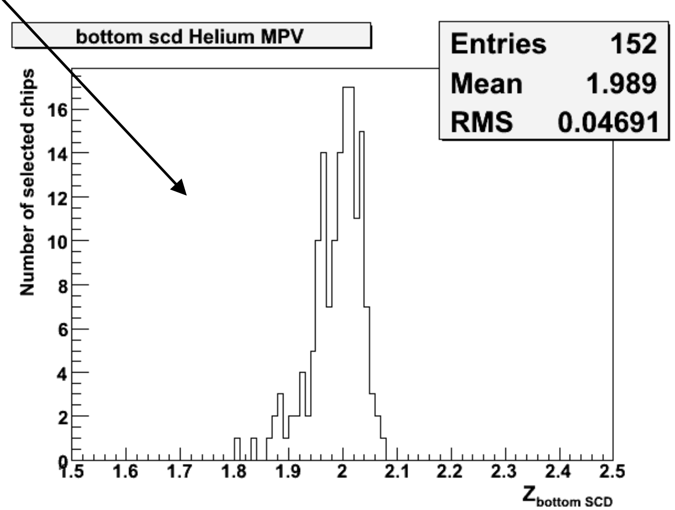
- Helium events were taken with special trigger for calibration
- Each sensor signal is well fit to Landau curve

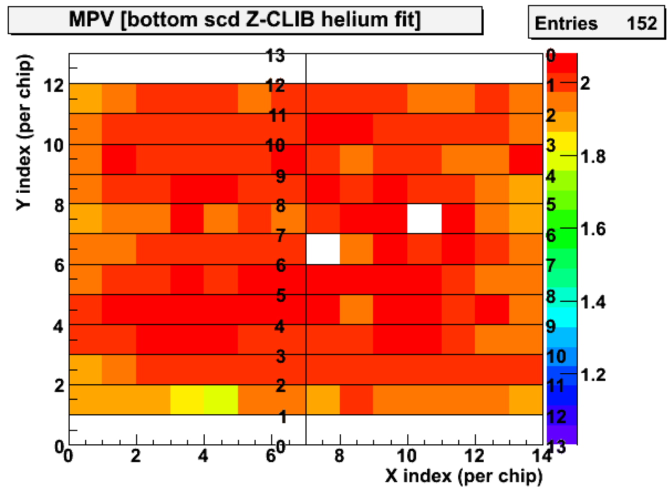
Distribution of Peak value of fit curve.

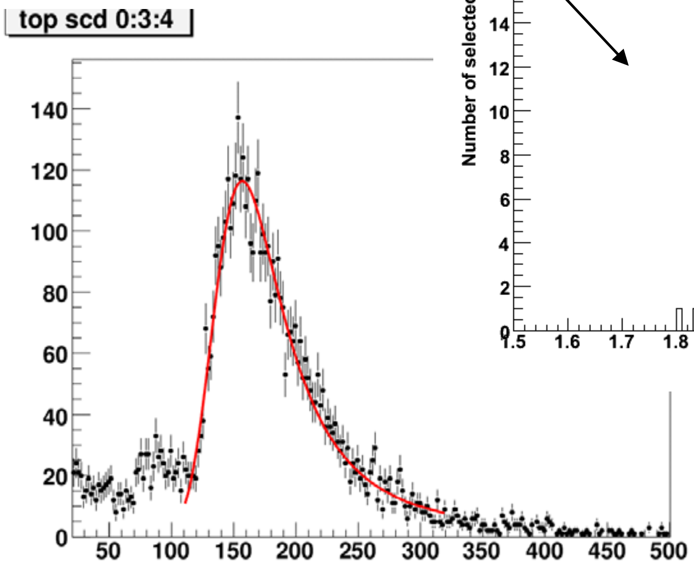
RMS ~ 0.023 * Z



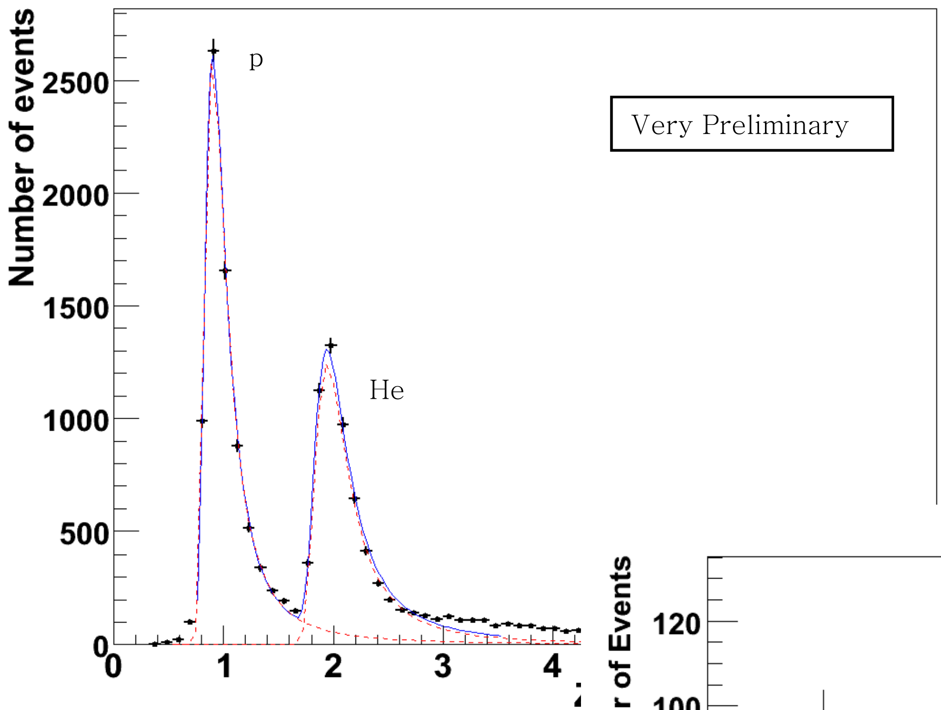


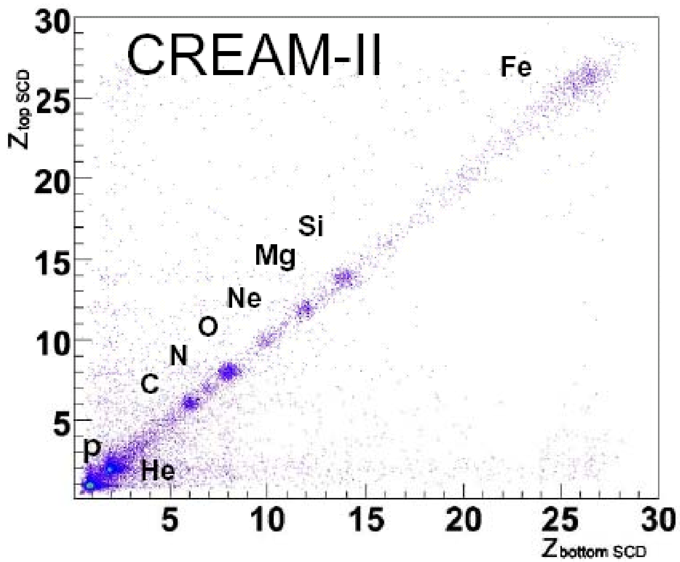


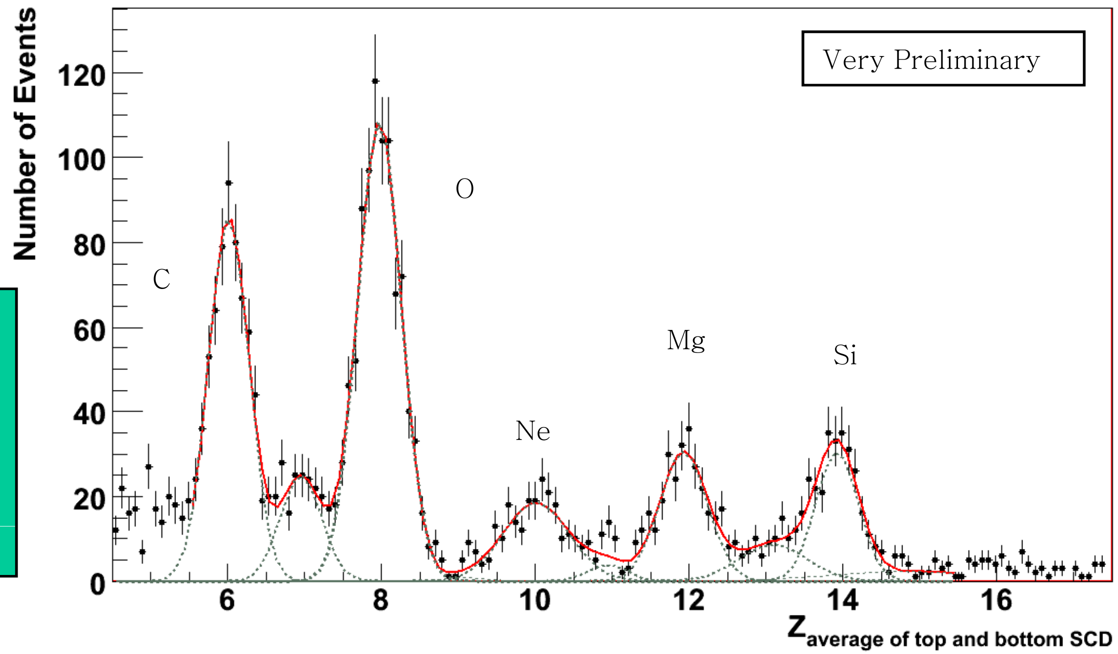




Charge Spectrum in the Flight Data







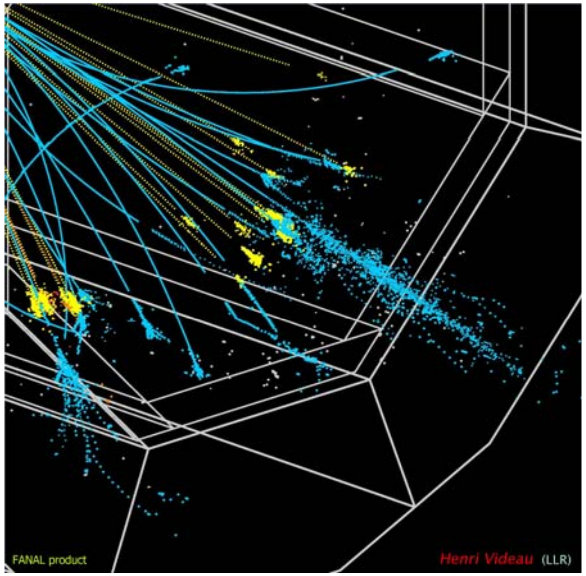
Clean signals up to Fe

Correlation between signals from top and bottom layers

(Data are not corrected for detector acceptance)

Silicon-W imaging calorimeter for ILC

Tungsten : small Moliere radius
Thin active layer with silicon → Sharp single particle shower



$$E_{\text{jet}} = E_{\text{charged}} + E_{\text{photons}} + E_{\text{neut. had.}}$$

$$\sigma^2_{E\text{jet}} = \sigma^2_{E\text{charged}} + \sigma^2_{E\text{photons}} + \sigma^2_{E\text{neut.had.}} + \sigma^2_{\text{confusion}}$$

Dean Karlen, LCWS 2002

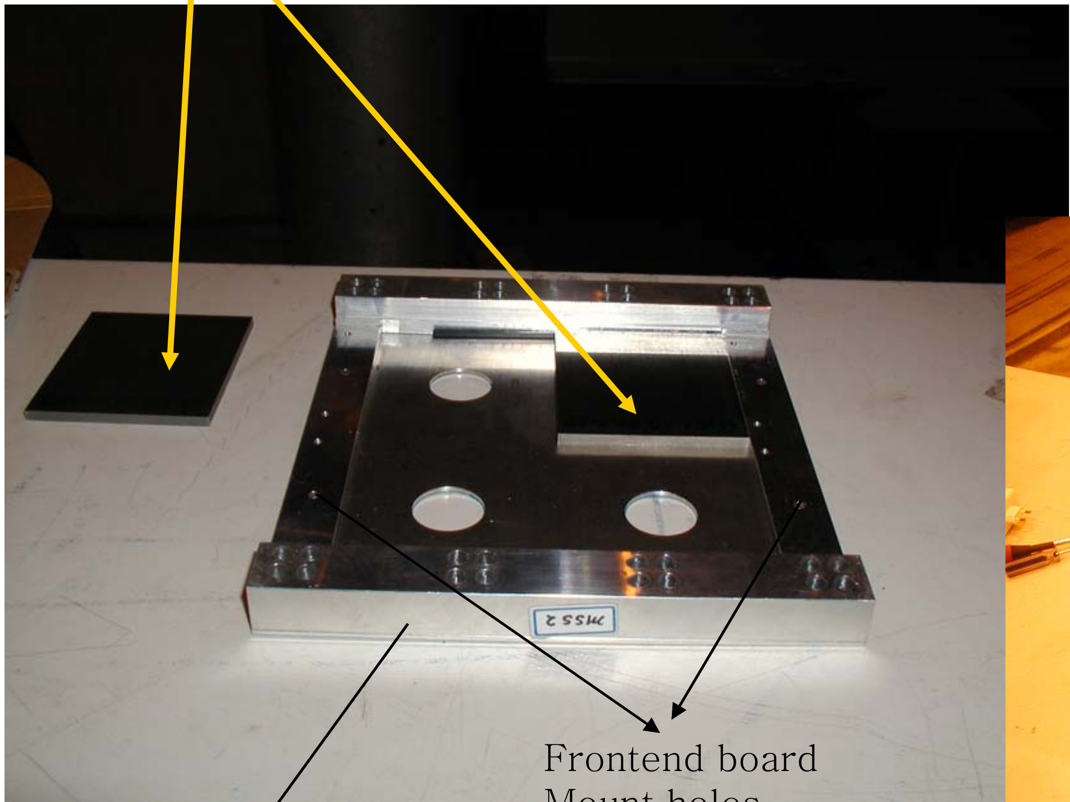
Single particle showers from photons, neutral hadrons have to be well separated in a jet.

For ILC Jets, about 26 GeV of photons have ECAL showers closer than 2.5 cm from a charged track → Segmentation in Silicon sensors ~ 10 mm

Test module Assembly

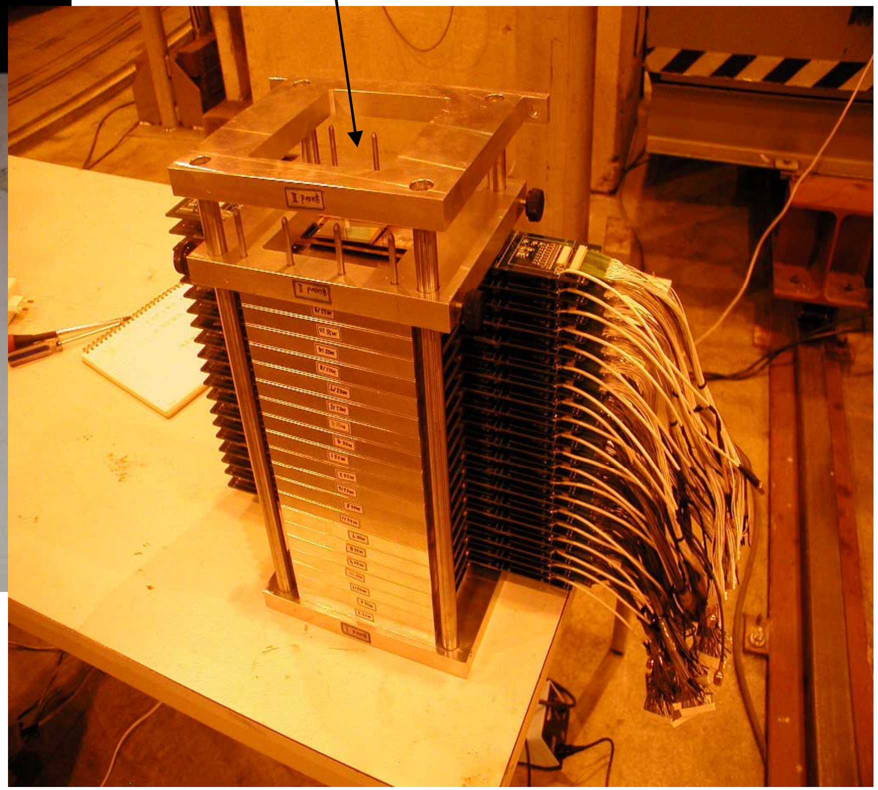
Tungsten

thickness ：3.5 mm (= 1 X0)
Size 65.5 mm X 57.5 mm (~ sensor size)

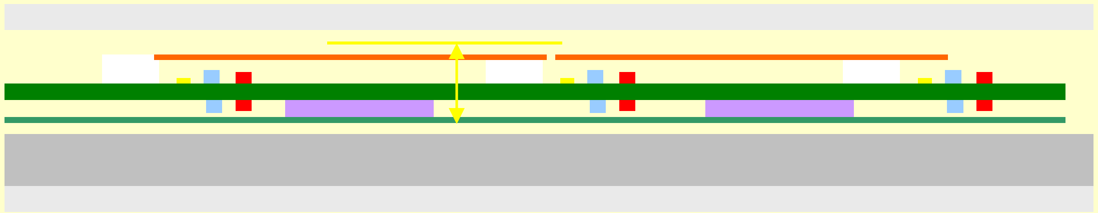


Aluminum Support of a Layer

Test Module：20 layers stacked



Thickness of an Assembled Layer

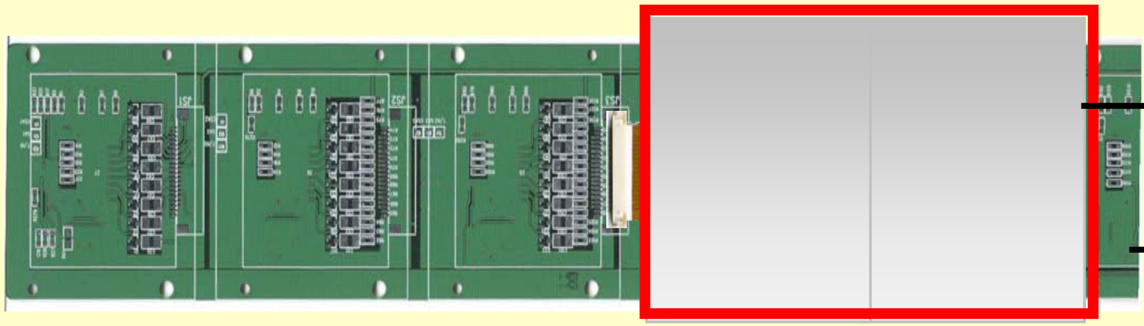


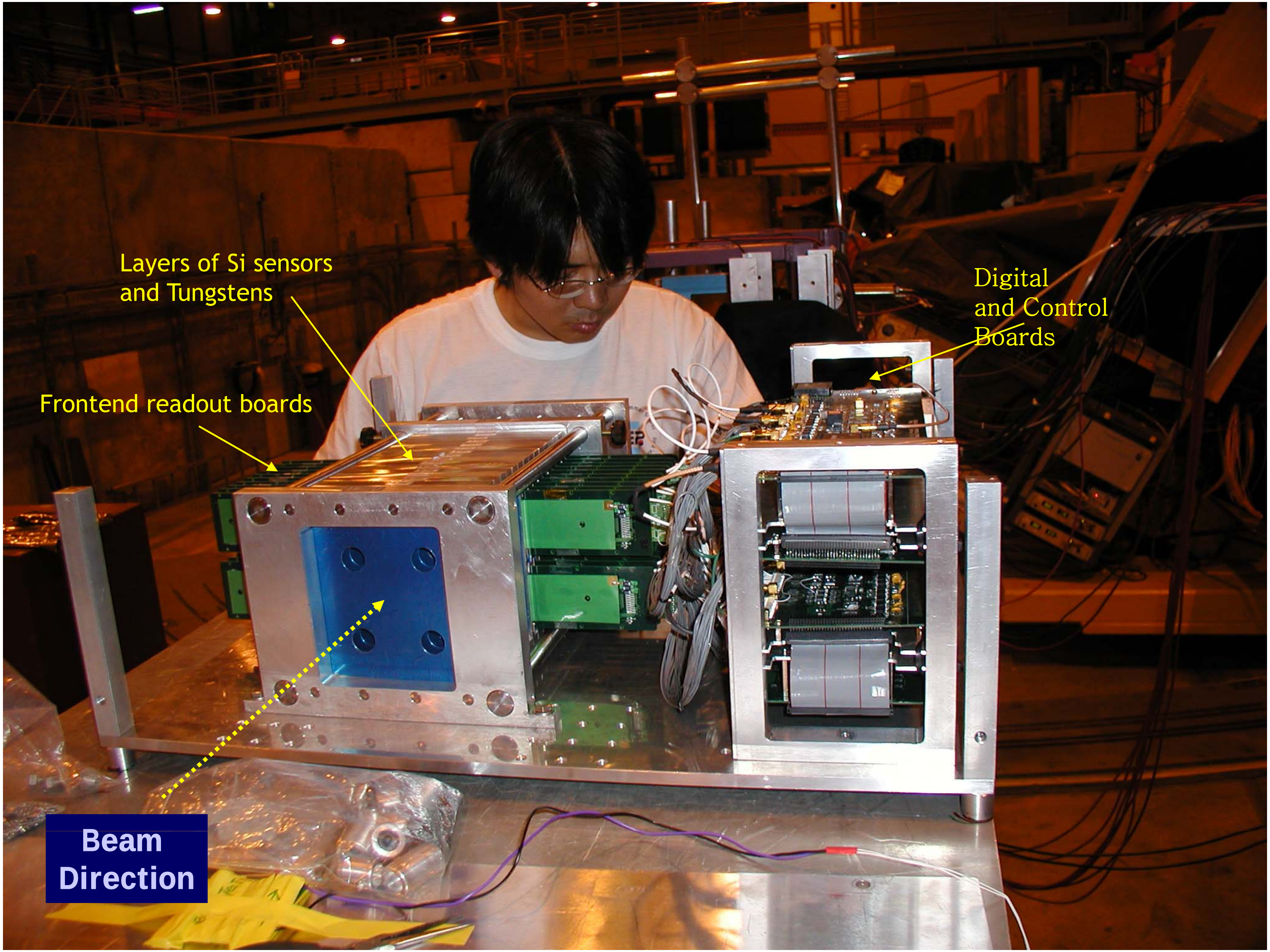
Connector 2.7 mm
Pcb 1.7 mm
Diode 1.15 mm
Shielding board 1mm
Capacitor 1.4 mm
Resistor 0.65 mm
CR 1.4 chip 2.45 mm

Aluminum	1.5 mm
Sensor and Readout	10 mm
Tungsten	3.5 mm

→ 15 mm

→|| ← 1mm inactive gap between sensors

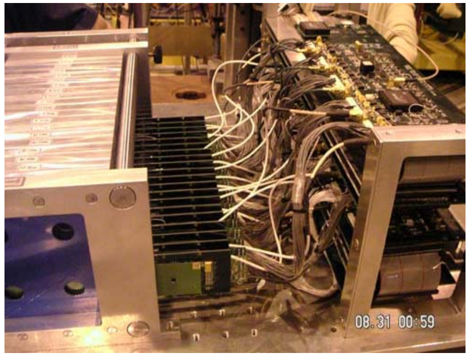



Layers of Si sensors
and Tungstens
Frontend readout boards
Digital
and Control
Boards
Beam
Direction

Test Module Setup

Geometry

- **Total 20 layers = 20X with uniform layer thickness**
- **Shower sampling at 19 layers with 2 sensors each layer.**
- **1mm gap between sensors**
- **Aligned beam center to the center of a sensor**

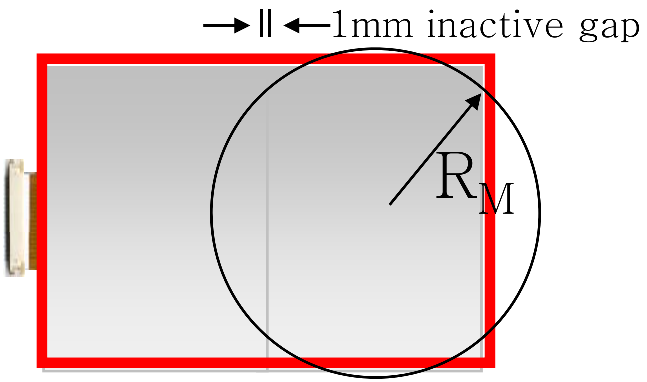


Effective R_M :~ 45mm

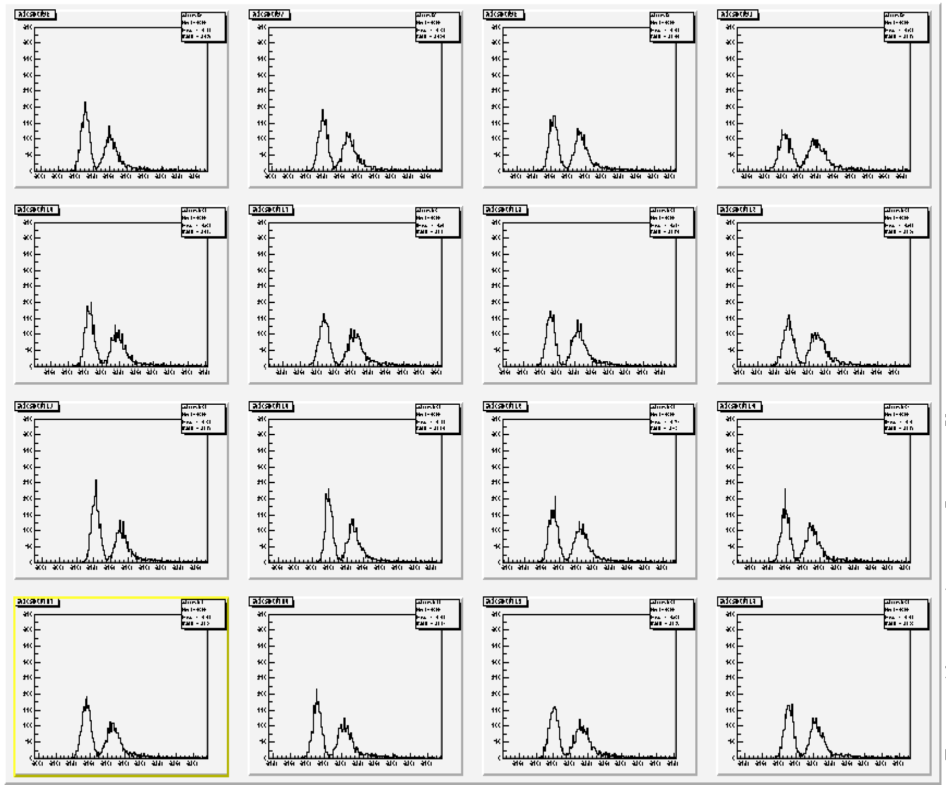
from volume ration of material

$$\rho_M = E_s \frac{X_0}{E_c} \qquad \frac{1}{X_0} = \sum_i \frac{V_i}{X_i}$$

-> **insufficient transverse shower containment**



Channel Scan for MIP calibration

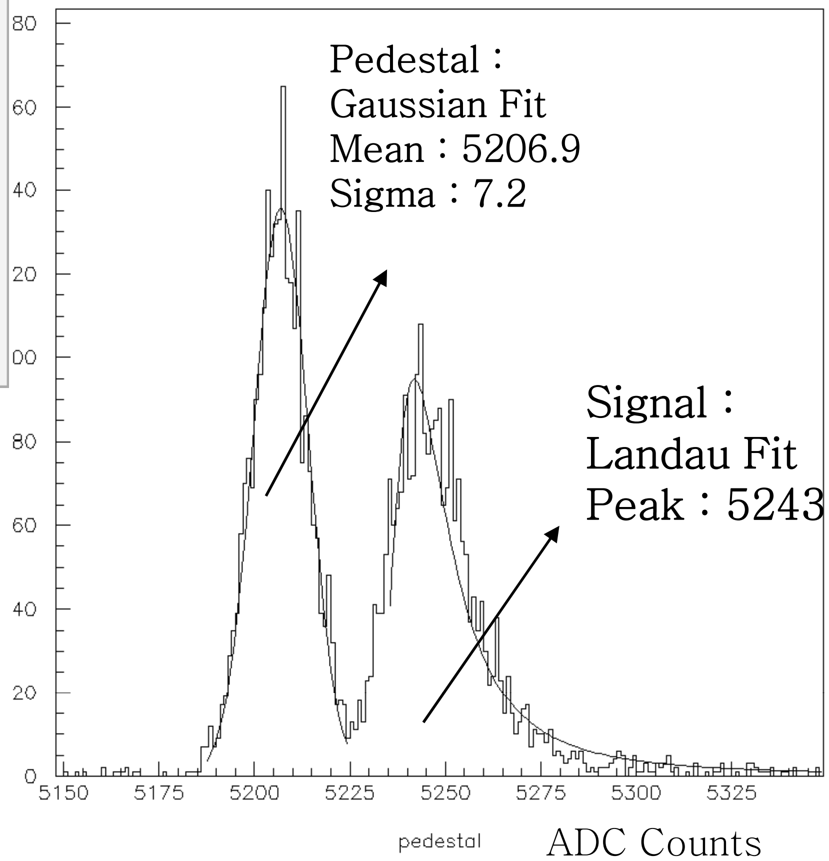


an example of a sensor with all good pixels

Scanned over all 640 channels with 100 GeV hadron Beam

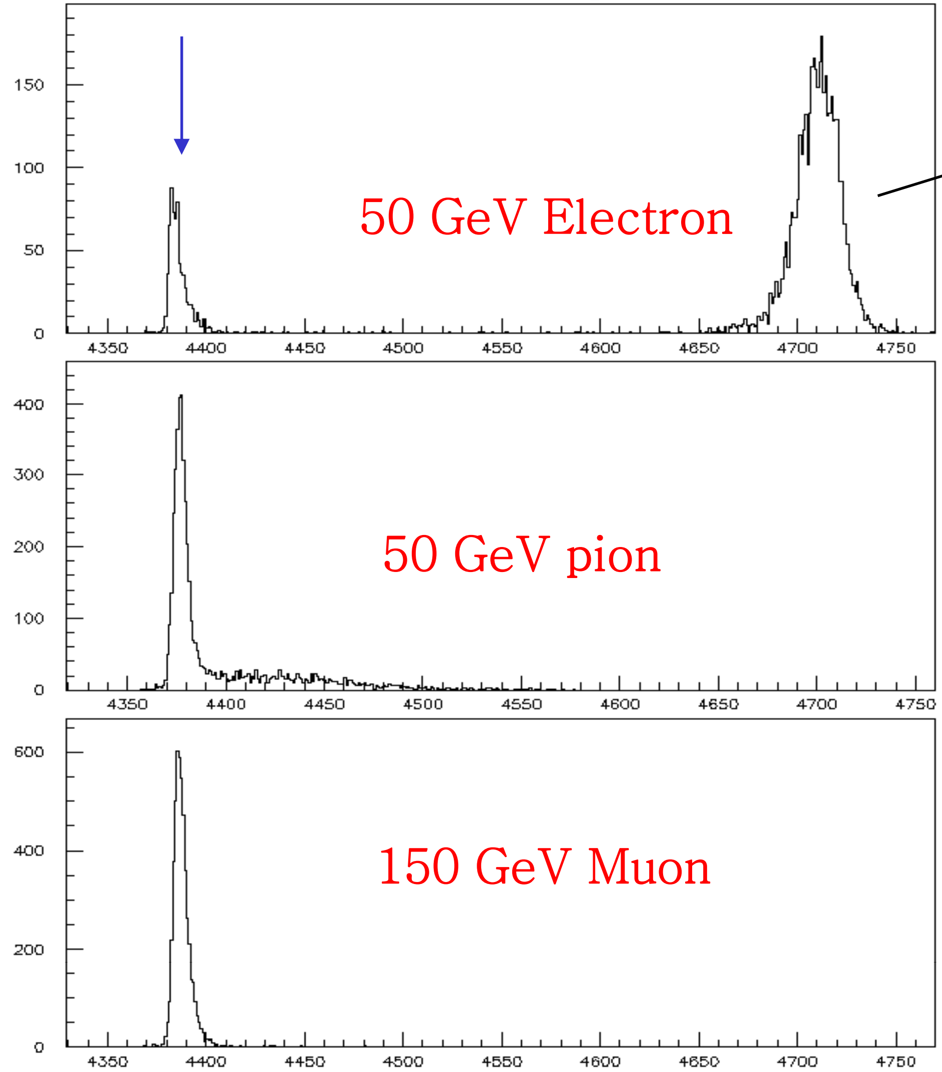
(no tungsten)

S/N = 5.2

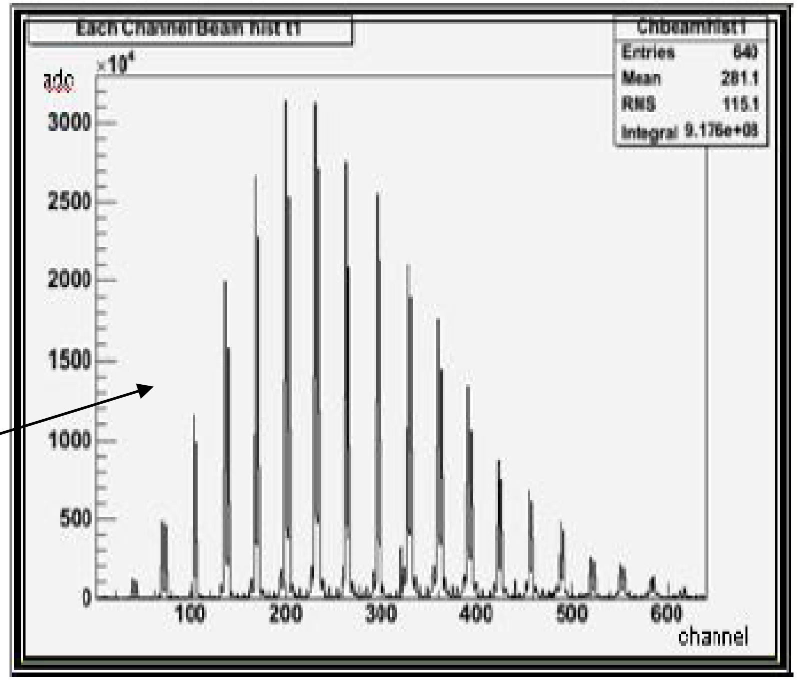


Detector Response to Different Particles

Random Trigger events (total pedestal)



Total ADC of an event / 640

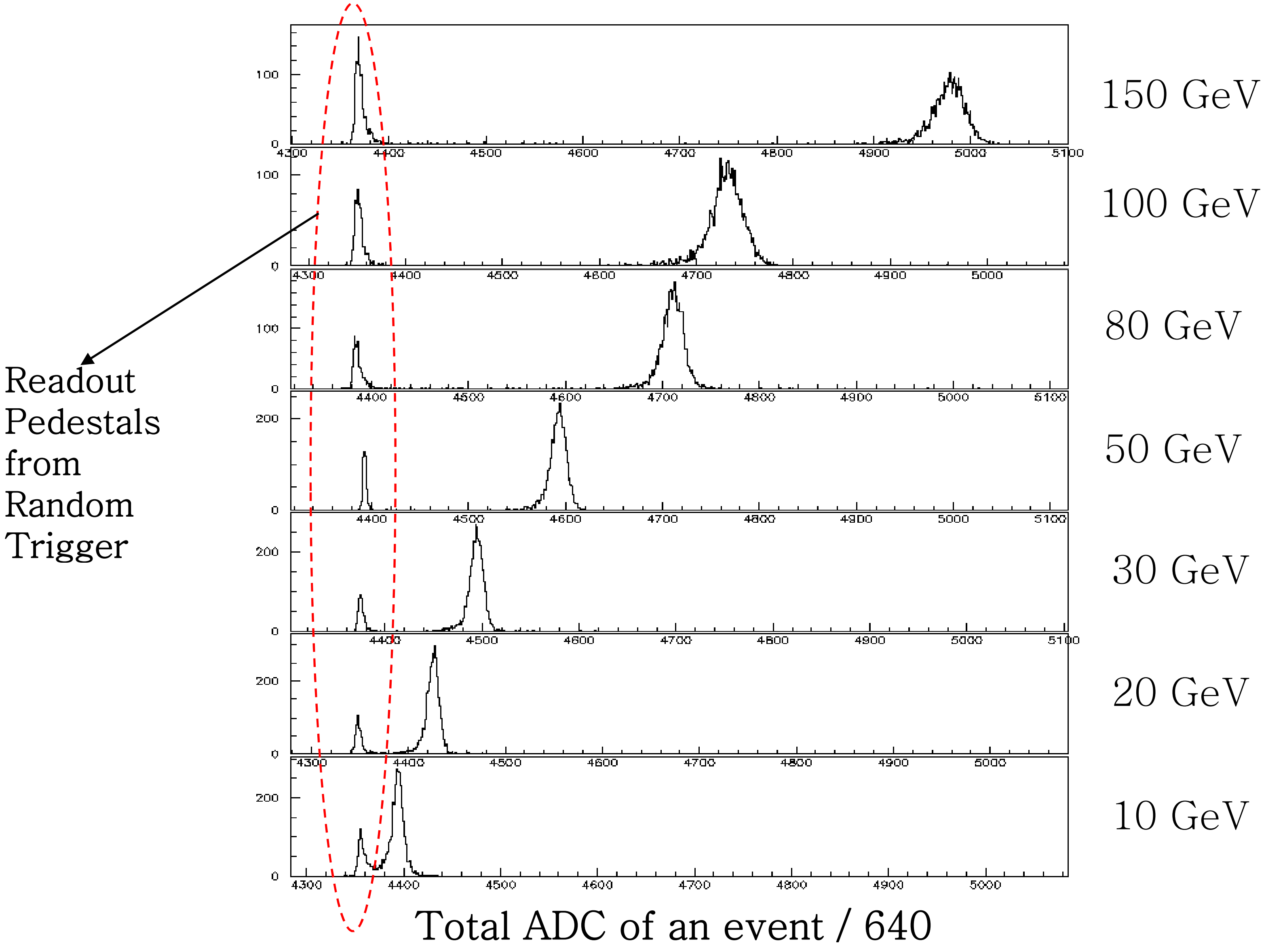


Online Shower Profile Monitor
Pedestal subtracted

First Analysis :
sum ADC counts of
all channels

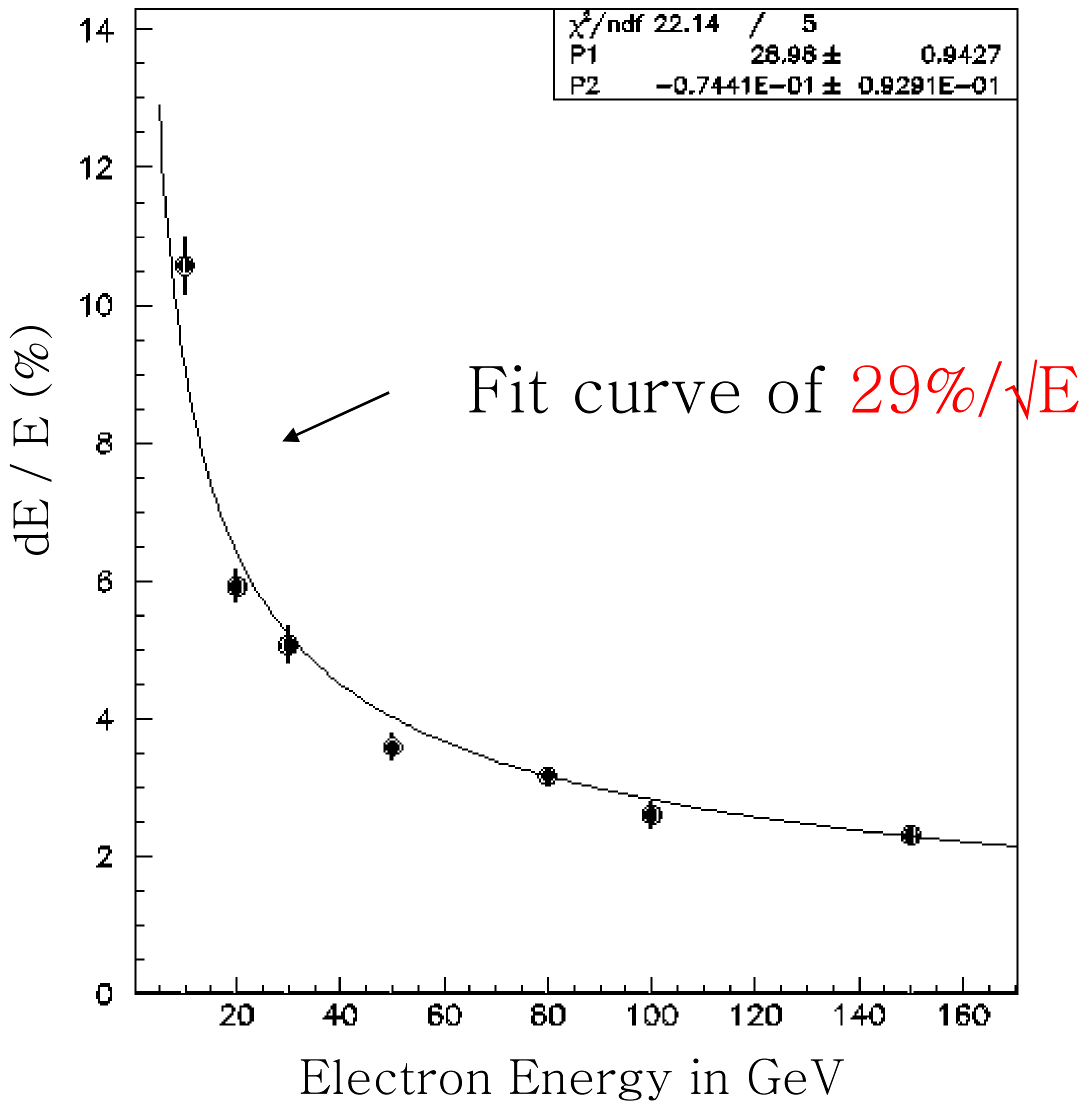
No rejection of dead, noisy channels, No gain calibration applied

Detector Response to Different e^- Energy Shower



Energy Resolution

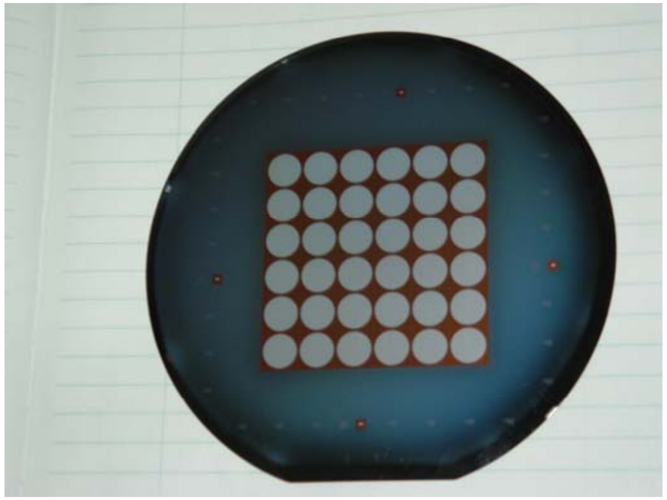
Preliminary



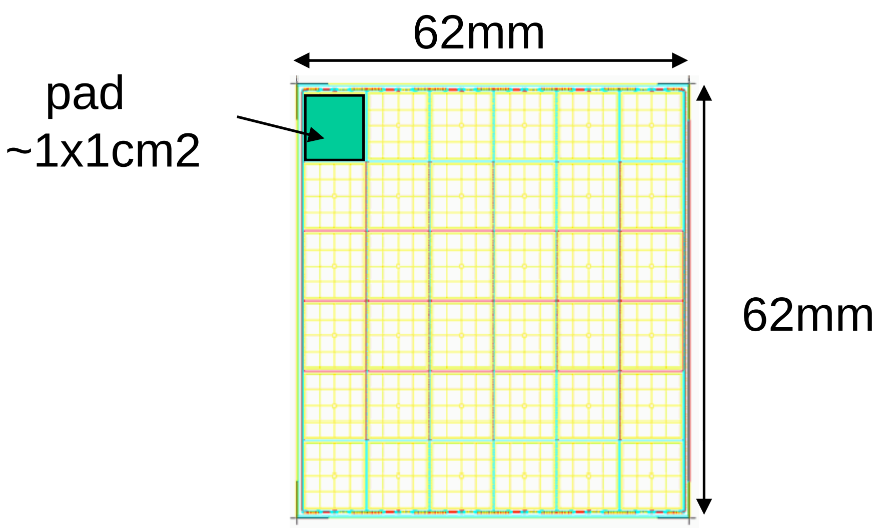
- Geant4 simulation of this setup taking into account only shower leakage gives 18%/√E.
- The effect of bad channels, gain calibration, and beam spread are not included here.
- Working on further analysis

New Silicon Sensors for ILC Si-W calorimeter (CALICE)

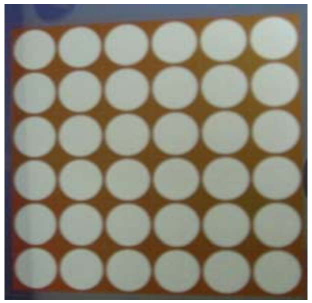
Silicon thickness : 525 micron
Size : Matrix of 6x6 pads, each pad have ~1cm^2
Nominal Bias 200V,
leakage @ 200 V < 300 nA for the full matrix
Wafers passivation for electrical contact with the glue EPOTEK E4-110 polytec (conductive glue with silver)



5" wafer



CALICE main pattern



6*6 pixels

Summary

- Design and production of a large number of silicon pixel sensors (more than 800) has been done.
- The sensor is 4*4 PIN diode array surrounded by 3 guard rings with each pixel size of 15*13 mm^2, fabricated from 380 um high resistivity wafer.
- Most pixels have a low and stable level of leakage current (I_d <10nA/cm^2) at the operational bias of 100V.
- Sensors showed excellent performance in charge measurement of high-energy cosmic rays in balloon-borne experiment.
- The same sensors were successfully tested in high energy beam test for Si-W imaging calorimeter R&D.