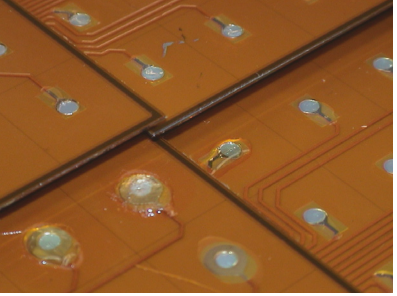
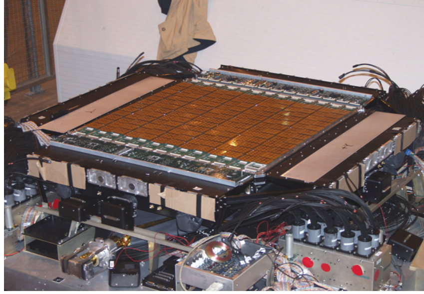


The Silicon Charge Detector for the CREAM Experiment

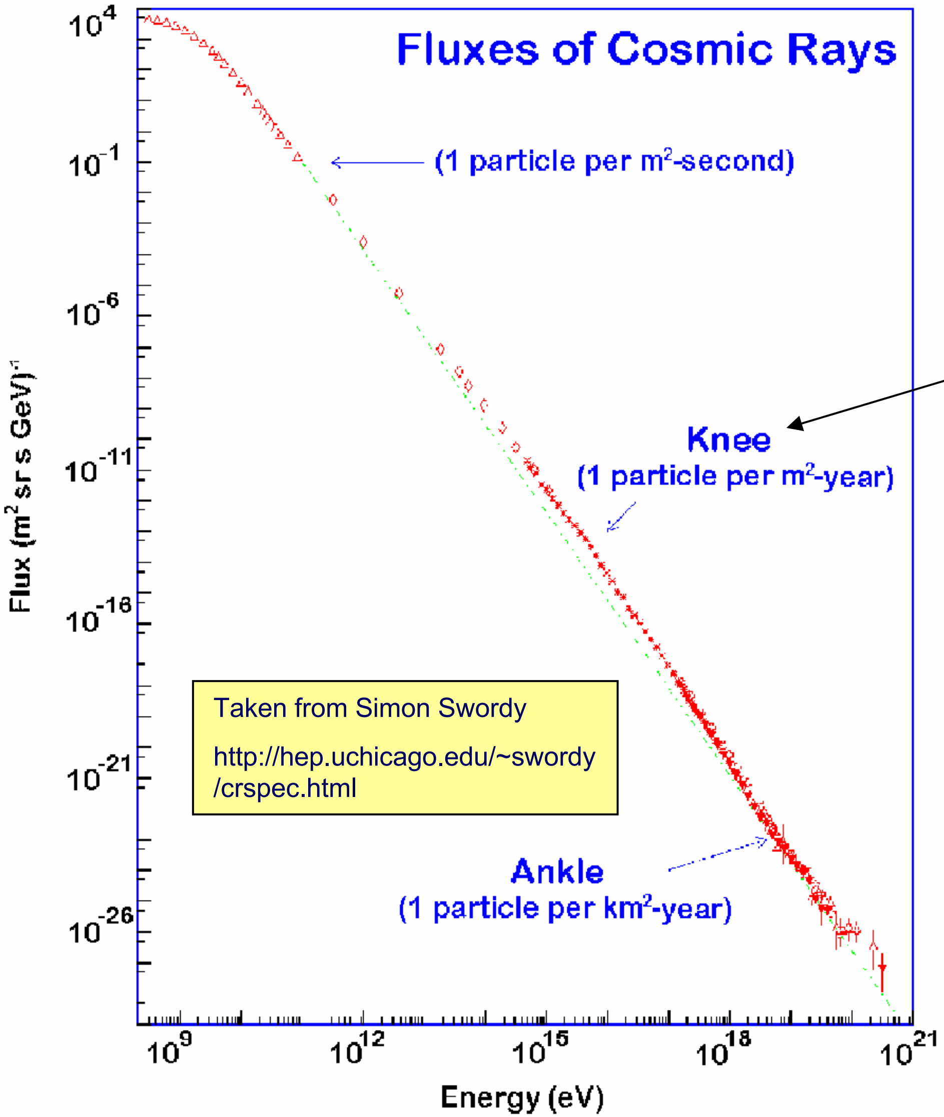


Park, Il H. (Ewha Univ., Seoul)
On behalf of the CREAM collaboration

7th Int. Conf. on Large Scale Applications and Radiation Hardness of Semiconductor Detectors, Oct. 5-7, Florence, Italy

- Cosmic rays
- The CREAM instrument
- Requirements in Silicon Charge Detector (SCD)
- Building of the SCD and CERN beam tests
- The first flight of CREAM and the performance of SCD

Cosmic Rays



- **1912 discovered by Victor Hess**

  (after Wilson & others)

- **1938 Pierre Auger** discovered

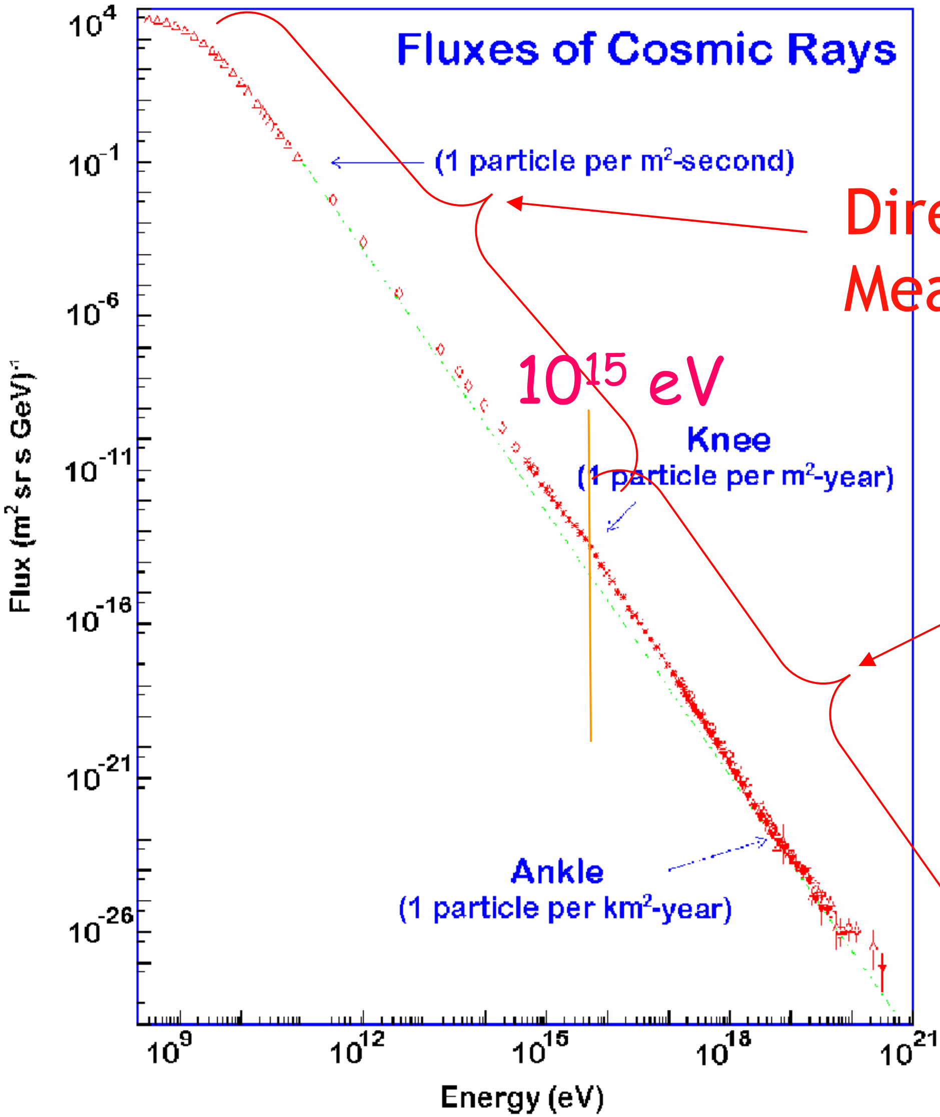
  Extensive Air Showers (EAS) (> 10^{15} eV)

- **Energy range:**

  ~ 10^9 eV to > 10^{20} eV

a compilation of direct and indirect cosmic ray observations integrated into a single spectrum

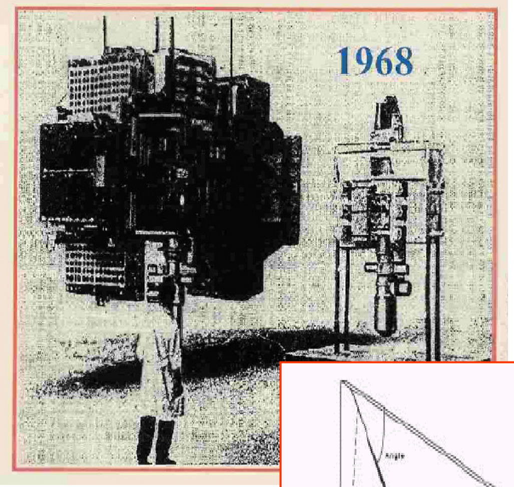
Direct Measurements of Cosmic Rays

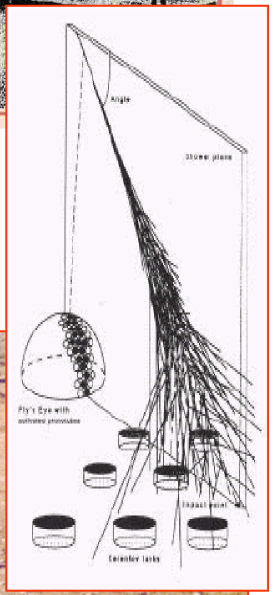


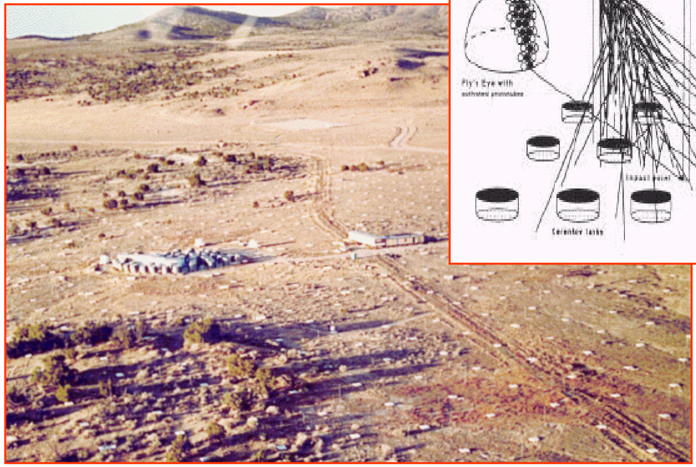
Direct Measurements

Indirect Measurements

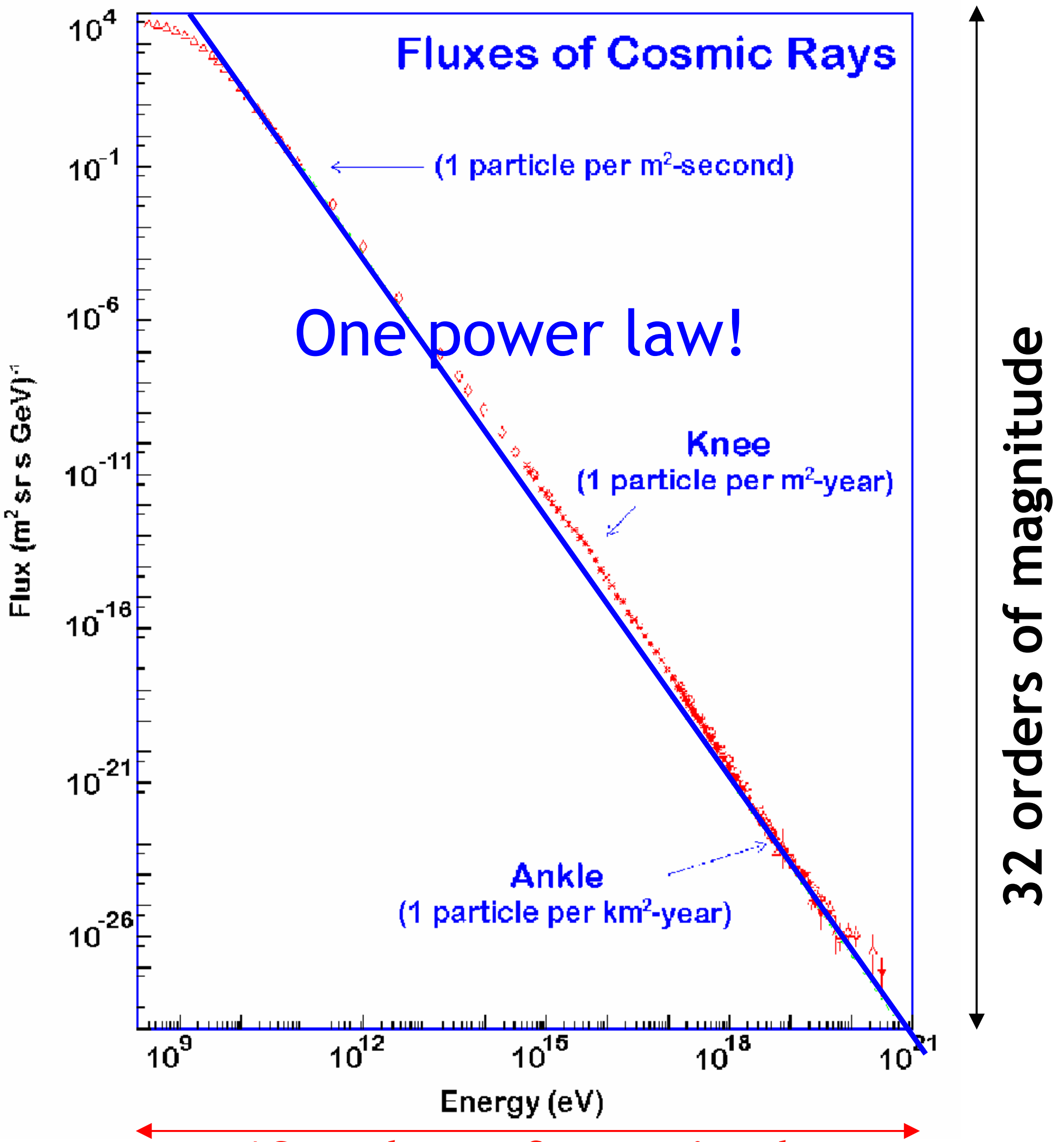
Proton Satellite Mission







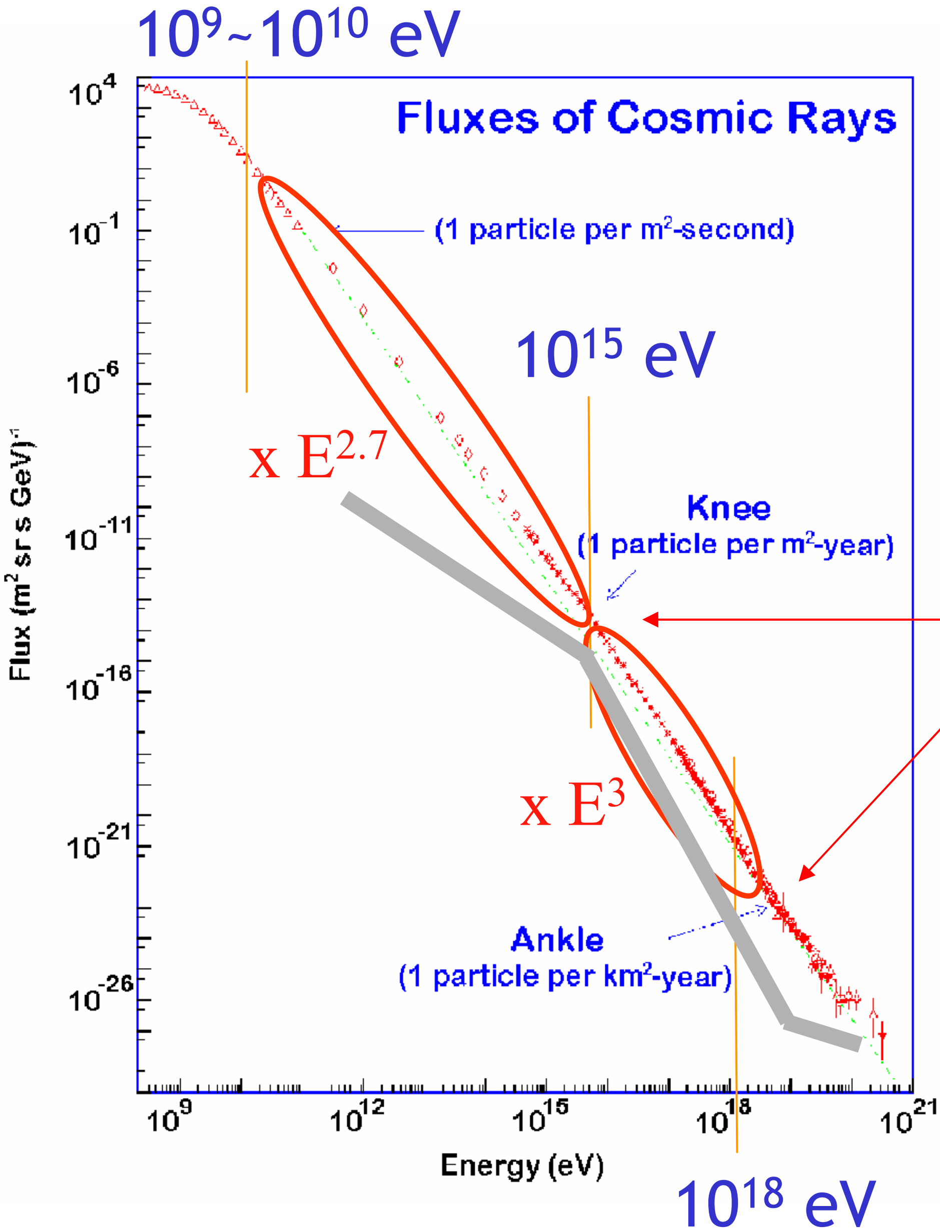
Grand-Unified Cosmic Ray Spectrum



Low energy cut off is due to solar magnetic fields.

The spectrum falls rapidly with energy, but it is a remarkably smooth curve over 12 decades of energy with a single power laws.

Knee and Ankle in Energy spectrum



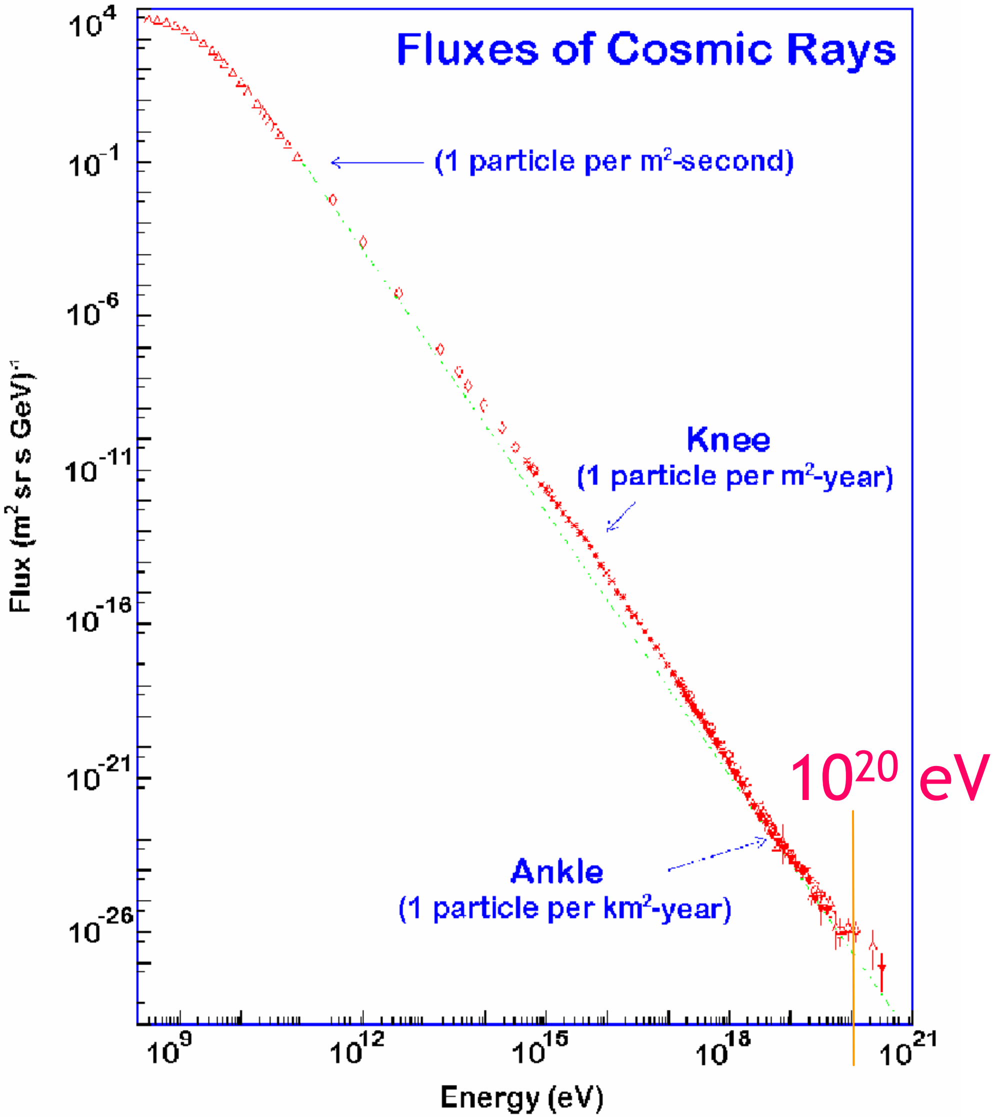
Why 2 power laws ?

Losses or coincidence ?

Features?

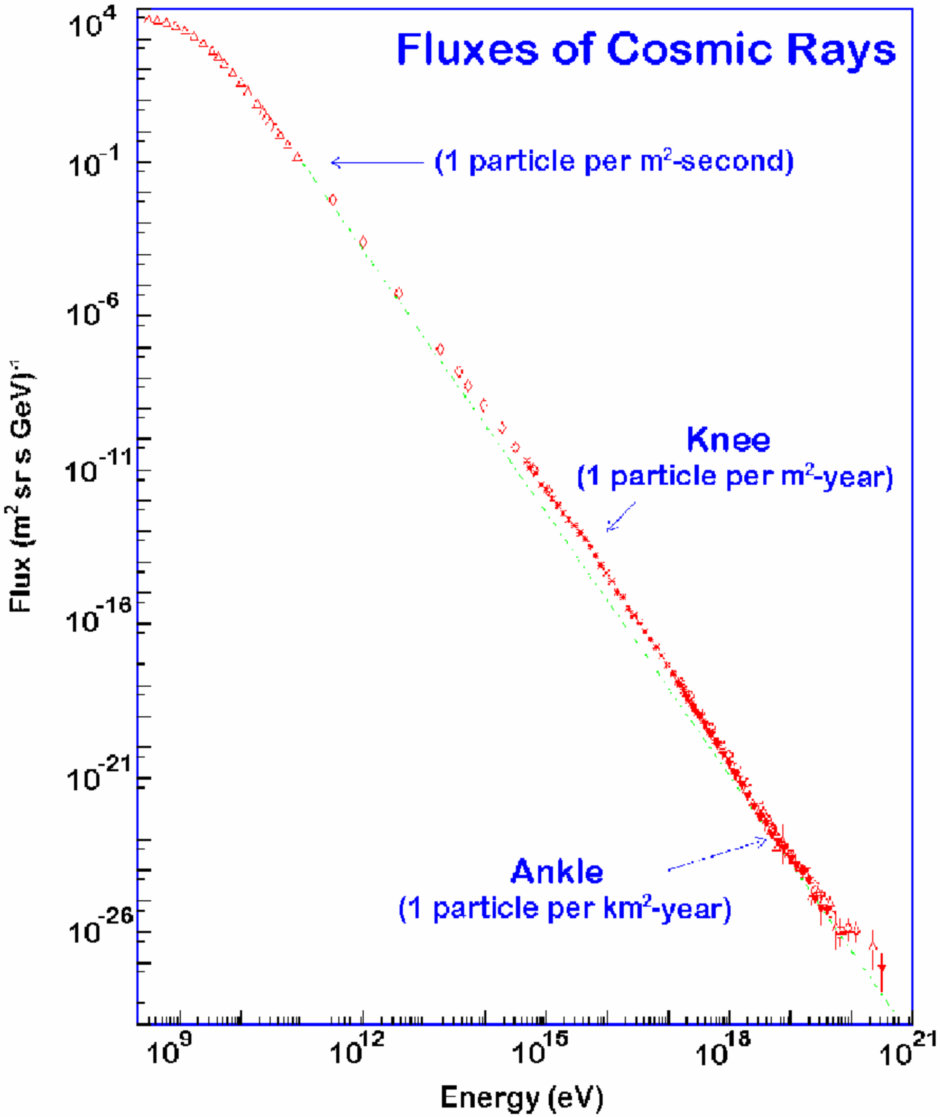
Change in underlying physics at the Knee and Ankle

What is the end of energy one can measure?



Is there an end?

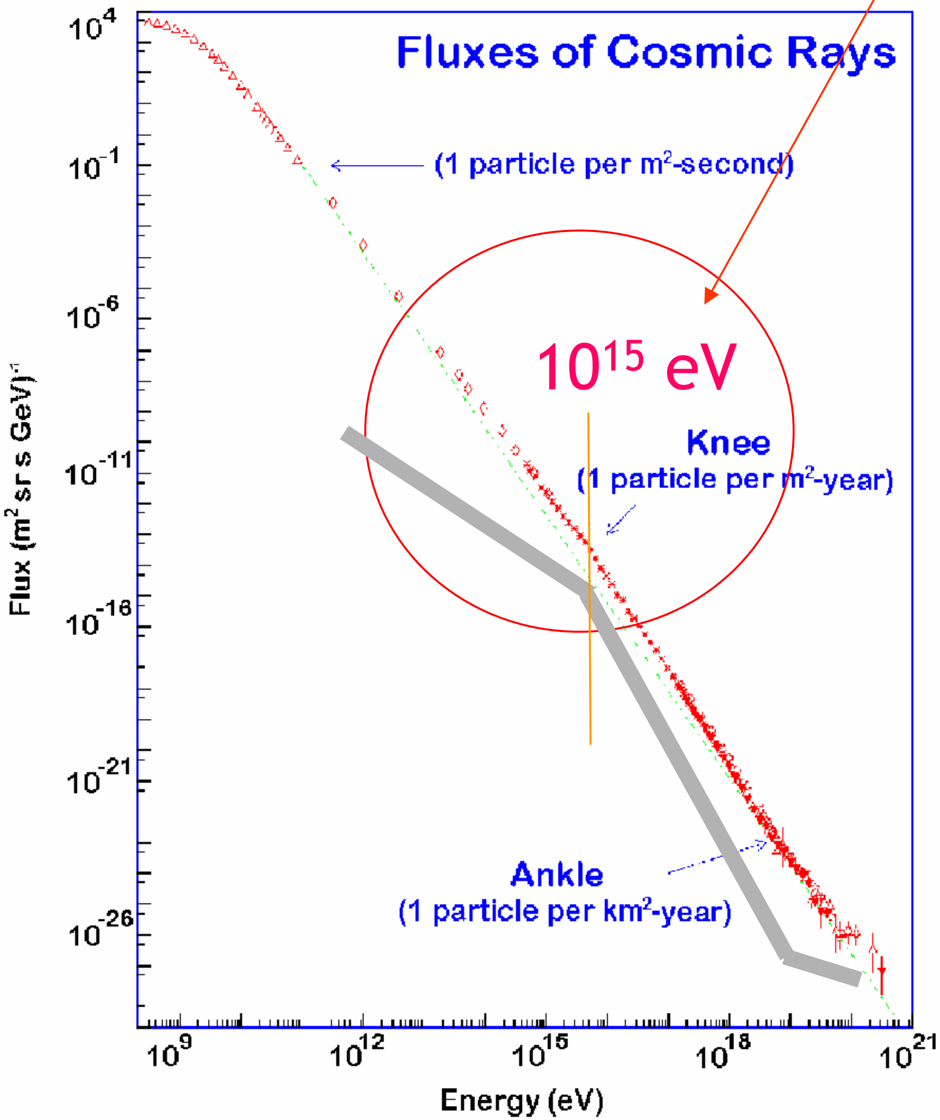
The Mystery of High Energy Cosmic Rays

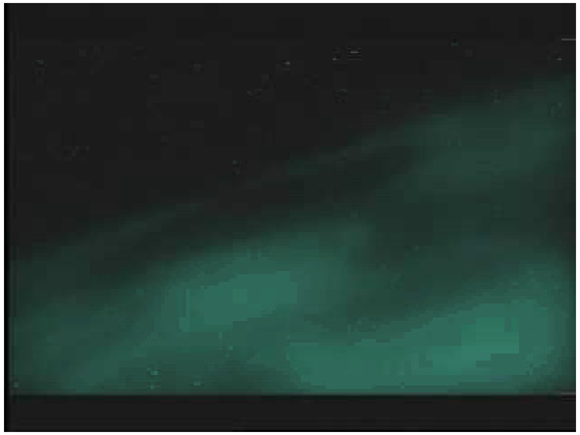


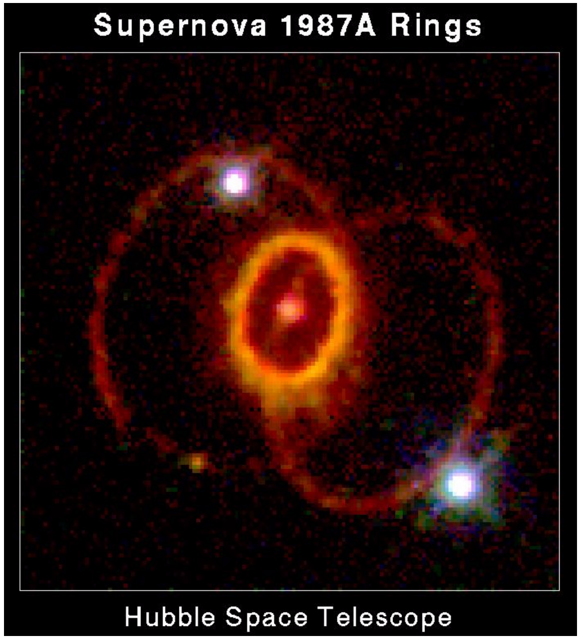
1. How are cosmic rays accelerated to such very high energies?
2. Where do they come from?
3. What s the composition?

- No one knows …
- 100 years old puzzle !

Supernova : Source up to the Knee energy ?



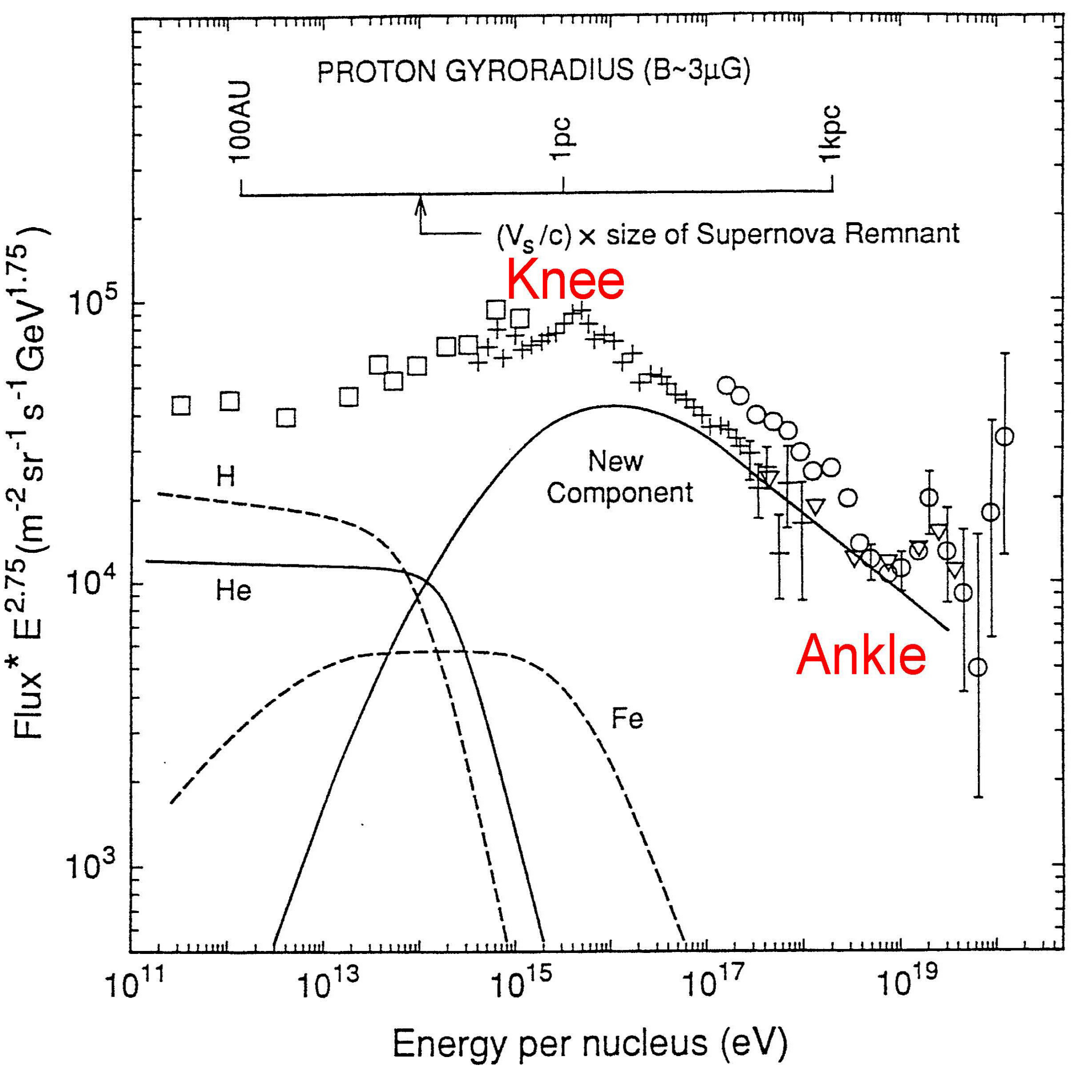


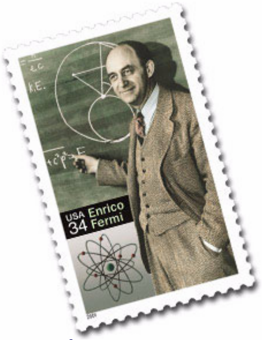


- Comprehensive understanding is left for future space mission

Supernova Remnant Shock Wave Model

Supernovae believed to be a source



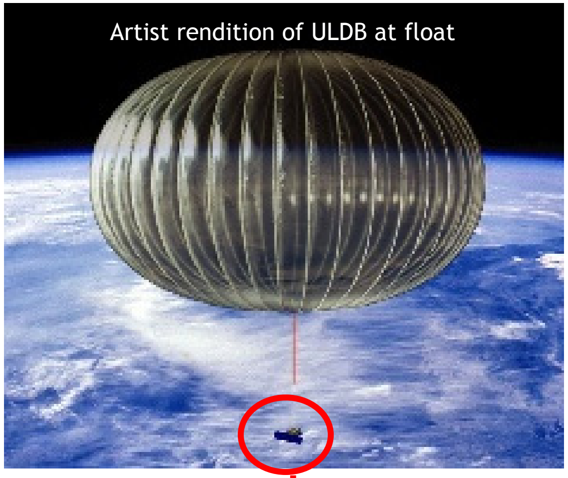


- Enrico Fermi first explained how cosmic rays are accelerated (1949)
  - Stochastic collision with moving magnetic clouds produced from SNR
- Acceleration limit in SNR shock wave near the knee
  - $2 \times 10^{14} \times Z$ (eV)
  - Change in elemental composition

CREAM

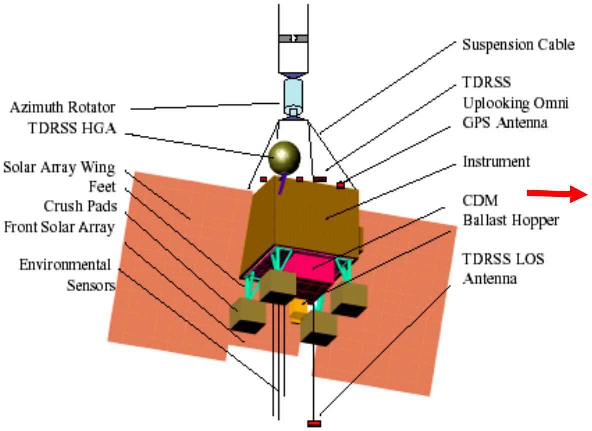
Cosmic Ray Energetics And Mass
An ULDB Cosmic Ray Astrophysics Mission

- ✓ **Elemental composition near the knee**
- ✓ **Direct measurement of Energy & Charge of primary cosmic rays**
- ✓ **Optimized arrangement of several components**



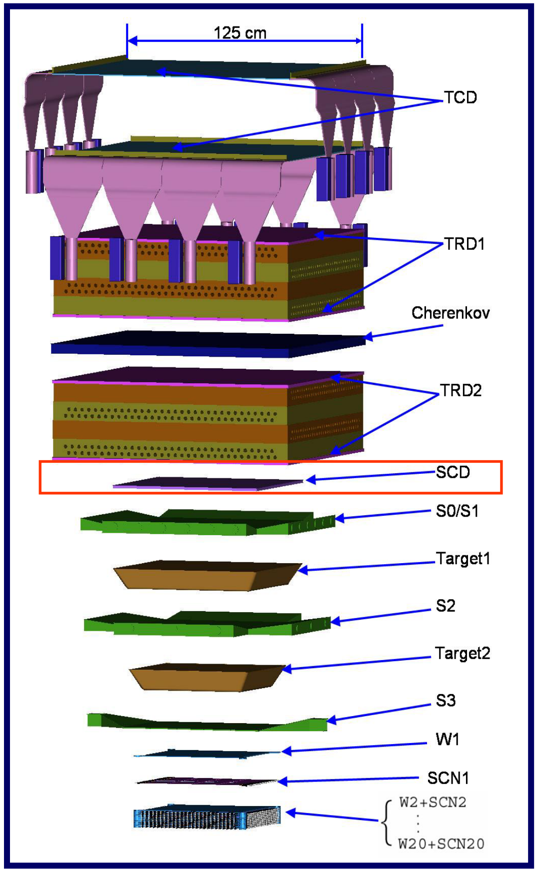
NASA ULDB Balloon

- **TCD (Timing based Charge Detector)**
  - Charge measurement
  - Plastic scintillator + PMT
- **TRD (Transition Radiation Detector)**
  - Measure Lorentz factor for $Z \geq 3$ for low energy
- **SCD (Silicon Charge Detector)**
  - *Charge measurement*
  - *Pixellated silicon*
- **HDS (Hodoscope)**
  - Track Reconstruction, charge identif.
  - Plastic scintillator + PMT
- **CAL (Calorimeter)**
  - Energy measurement for $Z \geq 1$
  - Scintillator-Tungsten with C targets



CREAM Payload

- **Energy measument**
  - **TRD, CAL**
- **Charge measurement**
  - **TCD, SCD**
- **Trigger**
  - Z-low trigger : CAL + TCD
  - Z-Hi trigger : TCD + TRD-chrenkov



CREAM Baseline configuration

CREAM-I Collaboration

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Northern Kentucky University, USA
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Kent State University, USA
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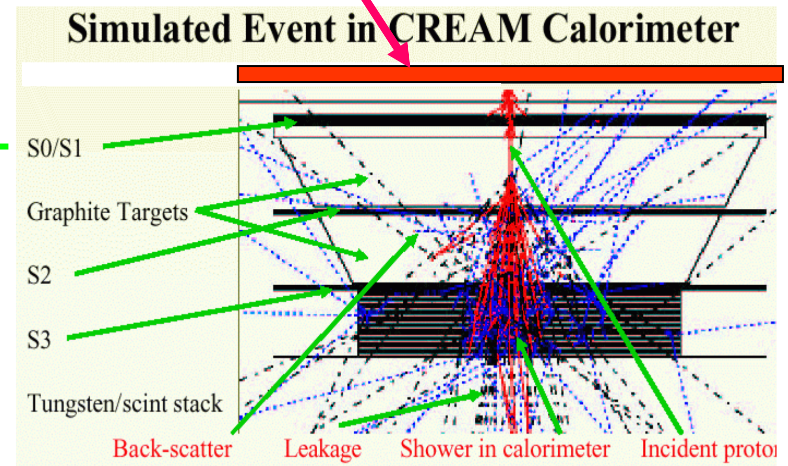
Kyungpook National University, S. Korea
K.W. Min
Korea Advanced Institute of Science and Technology, S. Korea

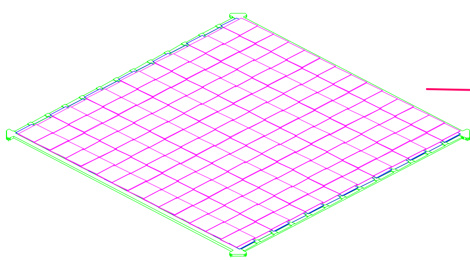
Requirements in SCD

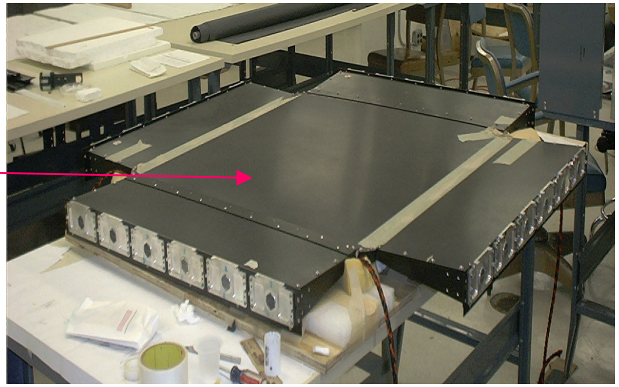
- Precision charge measurement
  - Charge resolution dZ = 0.2
  - Charge measurement up to Z=26 (Fe)
- Unambiguous backscatter rejection
  - Work in high backsplash from Calorimeter/Target

- Volume < 2 × 79 × 79 cm^3
- Number of channel < 3000
- Power budget < 50 W
- Weight < 12 kg
- Operate at low pressure (5 torr)
- Dead area free

Charge detector

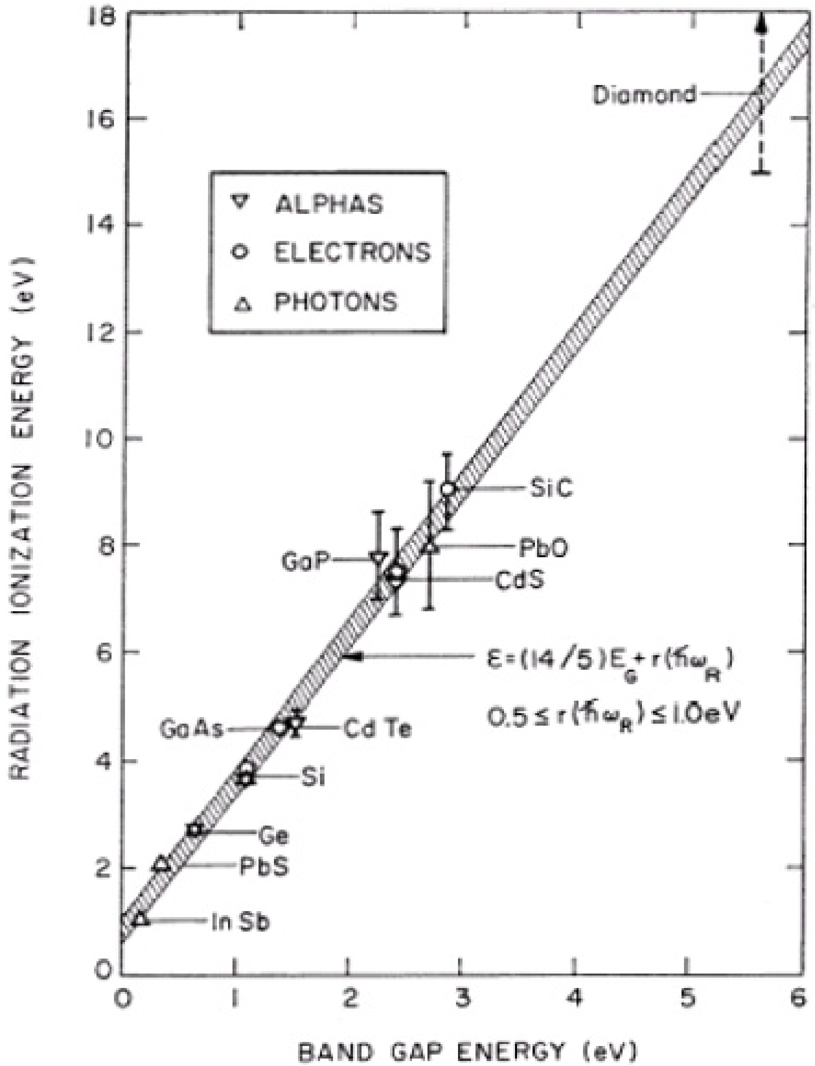






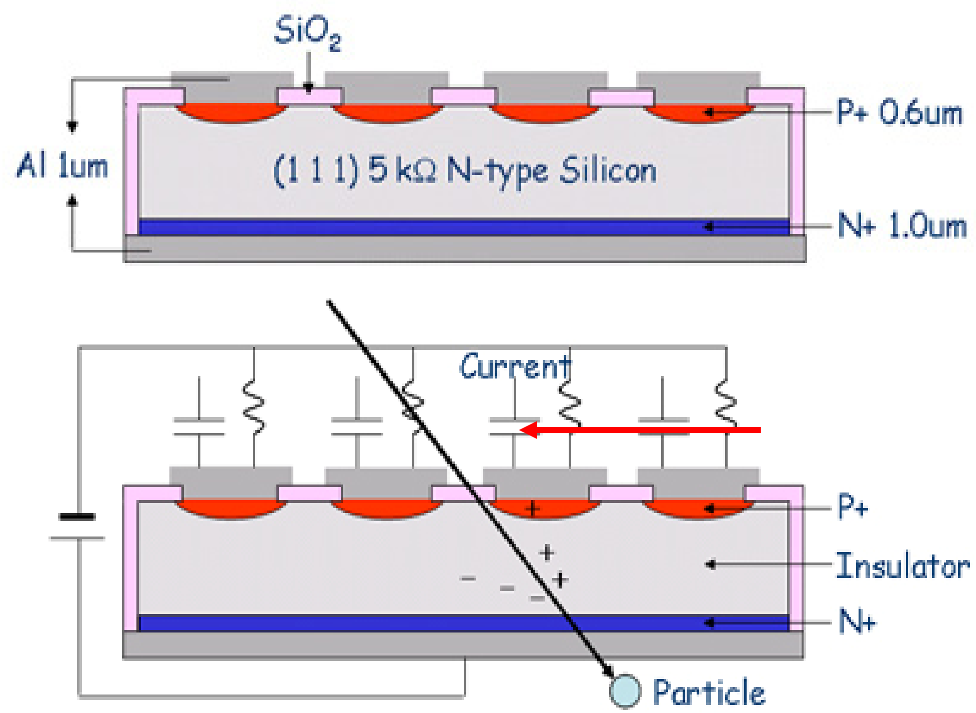
Choice of "pixellated silicon" detector

Why do we use silicon?



C. A. Klein, J. Applied Physics 39 (1968) 2029

- Low ionization energy
- High mobility
- Well proven technology



Principle of Charge Measurement using Silicon

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

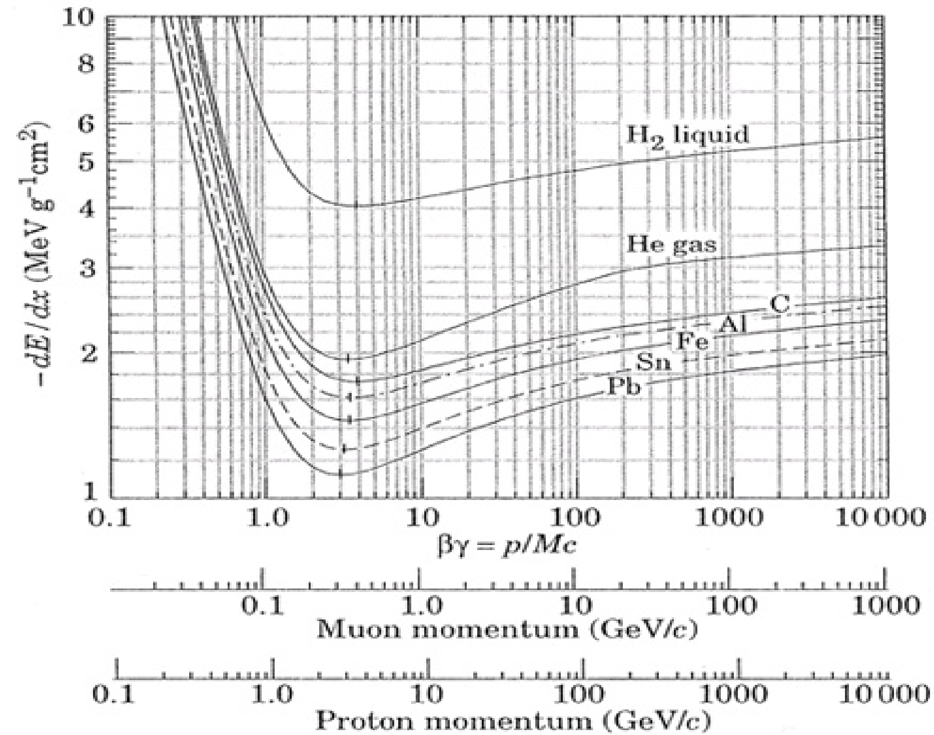
$$-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[\ln\left(\frac{2 m_e \gamma^2 v^2 W_{max}}{I^2} \right) - 2\beta^2 - \delta - 2\frac{C}{Z} \right]$$

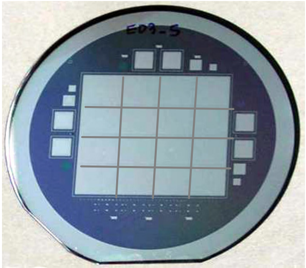
with $2\pi N_a r_e^2 m_e c^2 = 0.1535\ \mathrm{MeVcm^2/g}$

r_e: classical electron radius $= 2.817 \times 10^{-13}$ cm
m_e: electron mass
N_a: Avogadro's number $= 6.022 \times 10^{23}\ \mathrm{mol}^{-1}$
δ: density correction
ρ: density of absorbing material
z: charge of incident particle in units of e
$\beta = v/c$ of the incident particle
$\gamma = 1/\sqrt{1-\beta^2}$
C: shell correction
I: mean excitation potential
Z: atomic number of absorbing material
A: atomic weight of absorbing material
W_{max}: maximum energy transfer in a single collision.

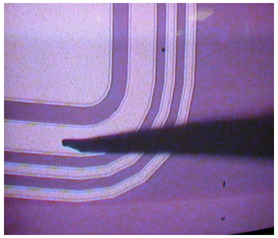
- For relativistic particle, energy deposit, dE/dx, doesn't depend strongly on Energy

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

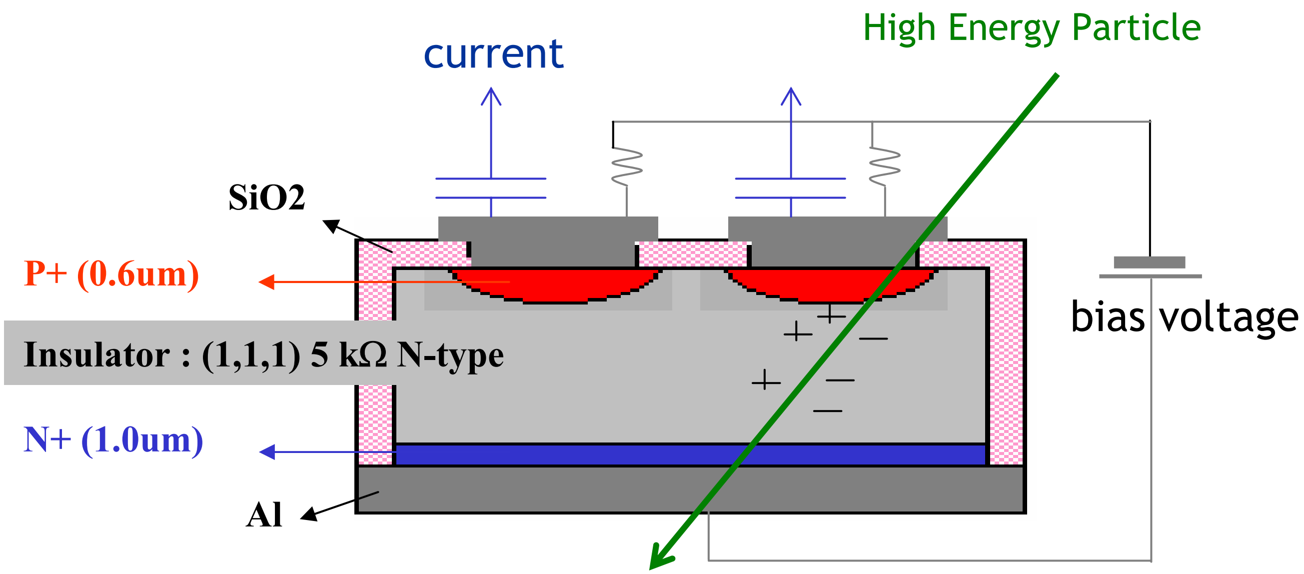




Silicon Sensor Structure



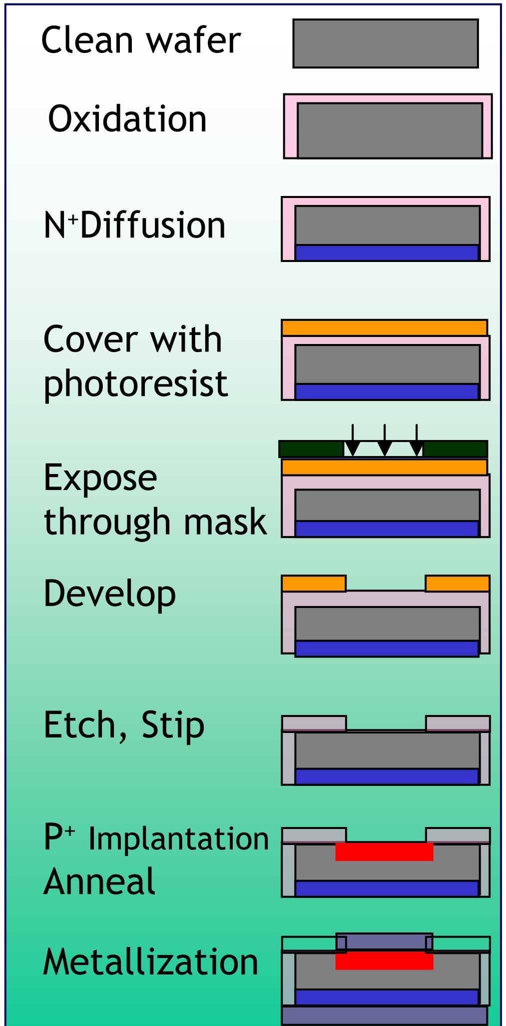
- PIN diode
- DC type
- Wafer: (1,1,1) type, 380 um, 5”, double polished, Wacker
- P+ implantation process, while N+ diffusion process
- Three guard rings



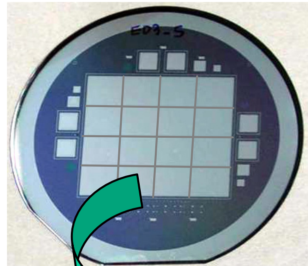
Silicon Sensor Fabrication

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

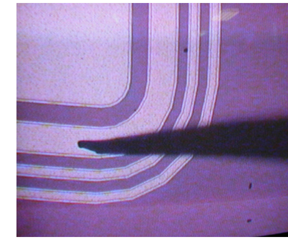
PIN diode structure

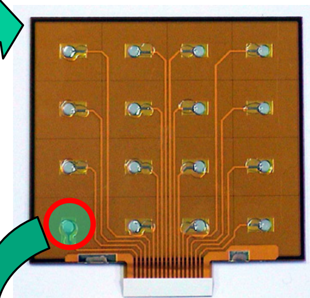


Fabrication process



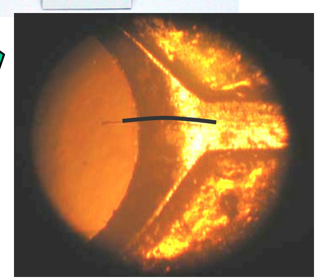
Fabricated sensor
Wafer size : 5 inch
thickness: 380 um
Pixel size : 1.55 × 1.37 cm^2
Array : 4 × 4 matrix





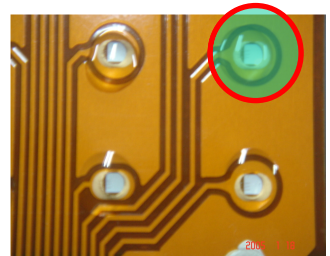
Sawing / attach Kapton tape
for connection to readout

✓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

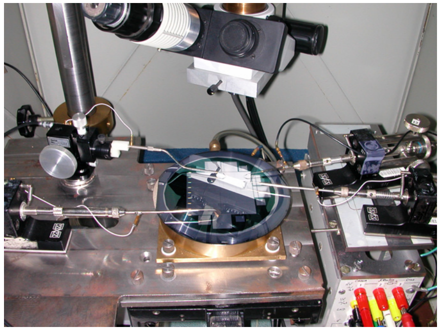


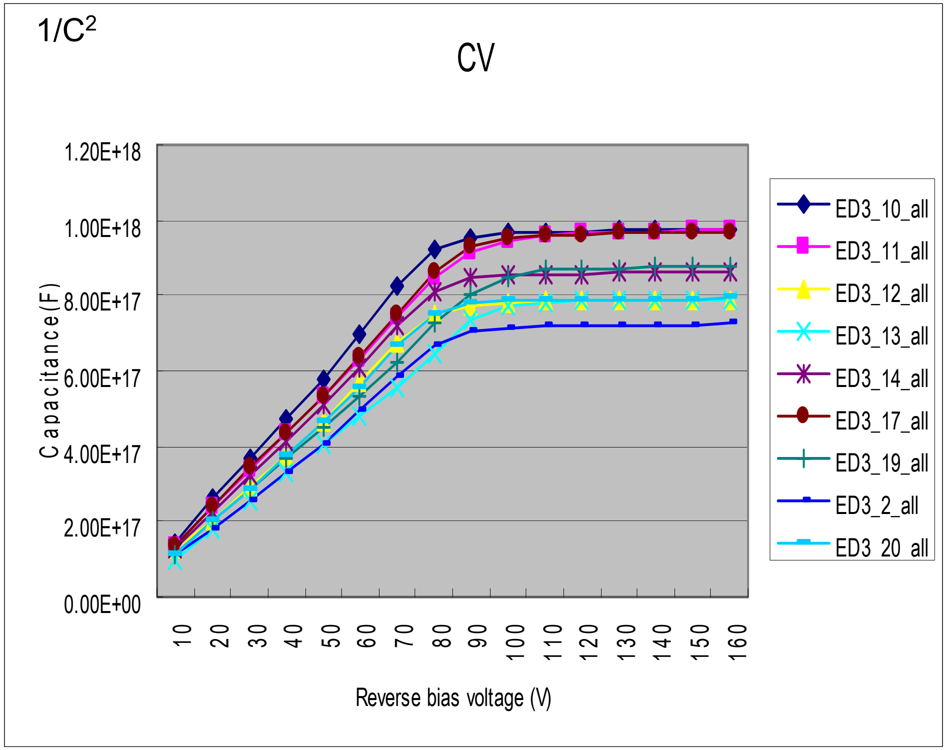
Glob Top
for protection and preservation
of bond wire

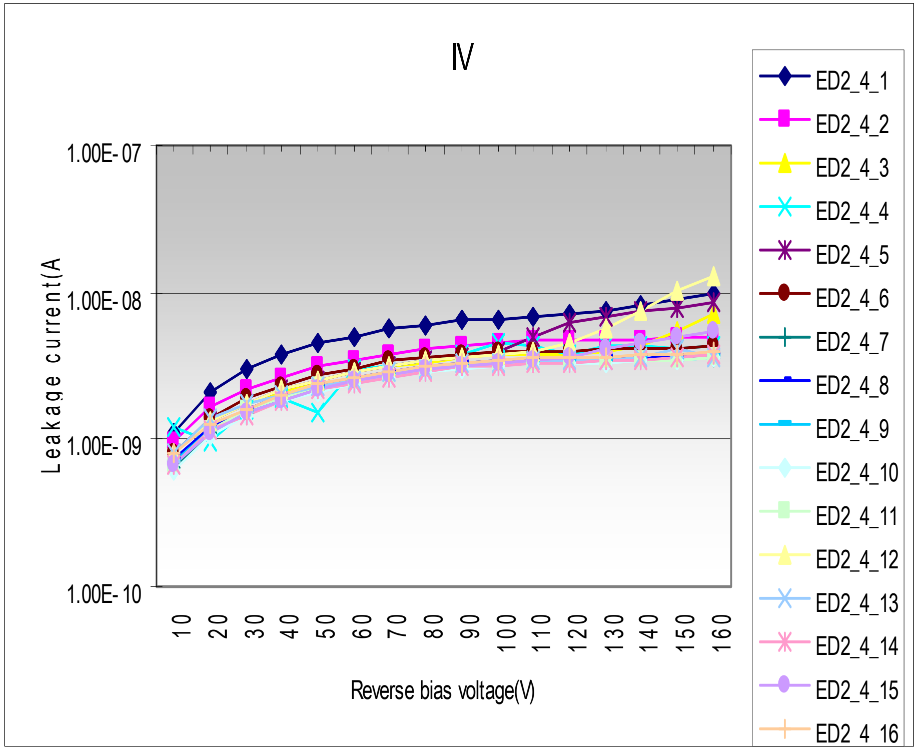
✓Coating
SJC Polychemicals, DCE, DP100

SCD Sensor Performance

$I_{Leakage}$ and Capacitance Measurement





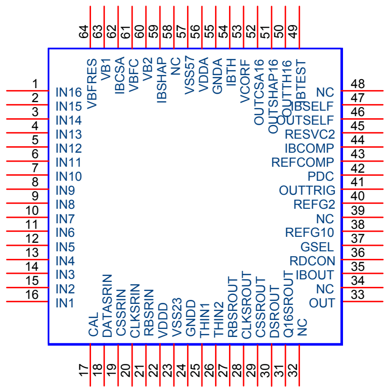


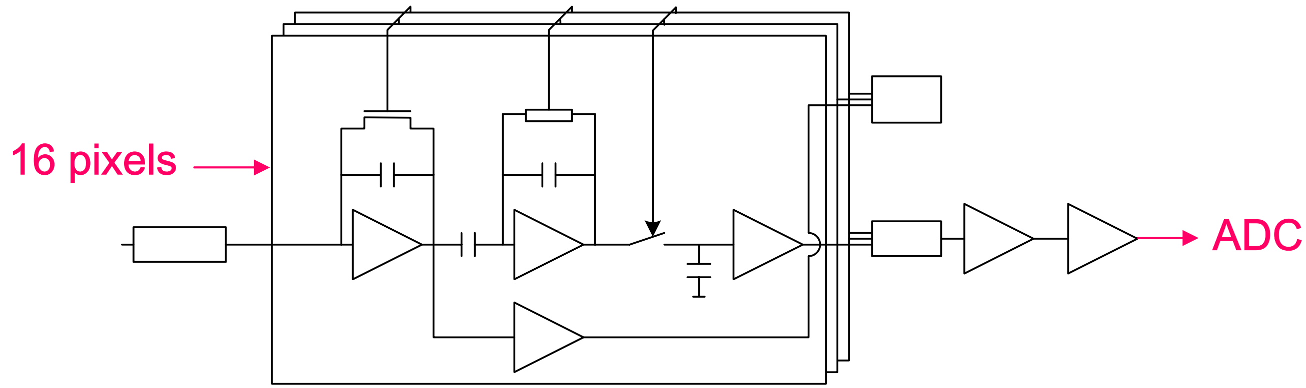
Find the full depletion voltage by measuring capacitance of sensor

- **Leakage current about <u>3 nA per pixel</u> at full depletion voltage**
- **Yield ~90%**

Analog Electronics (Frontend Readout)

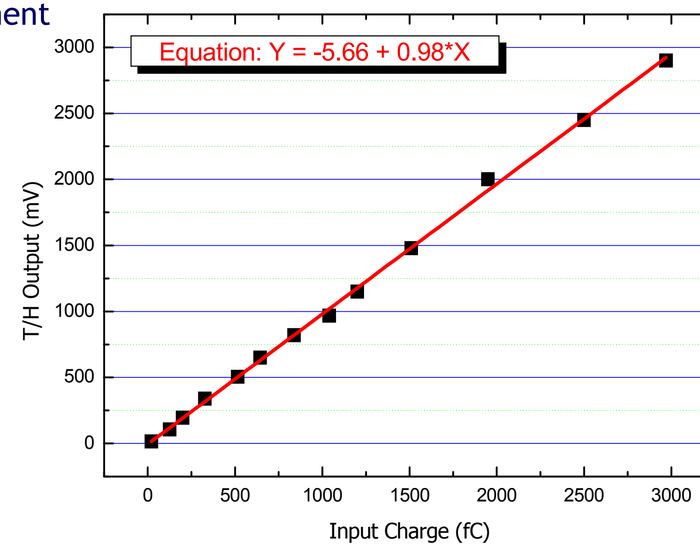
Frontend readout chip : CR1.4

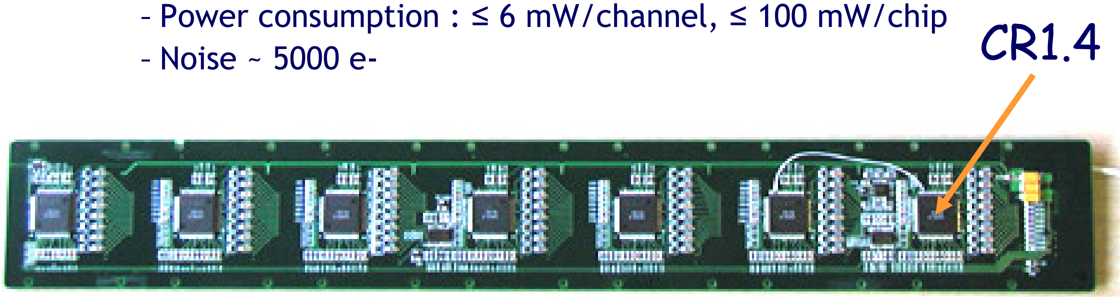




CR1.4 ASIC

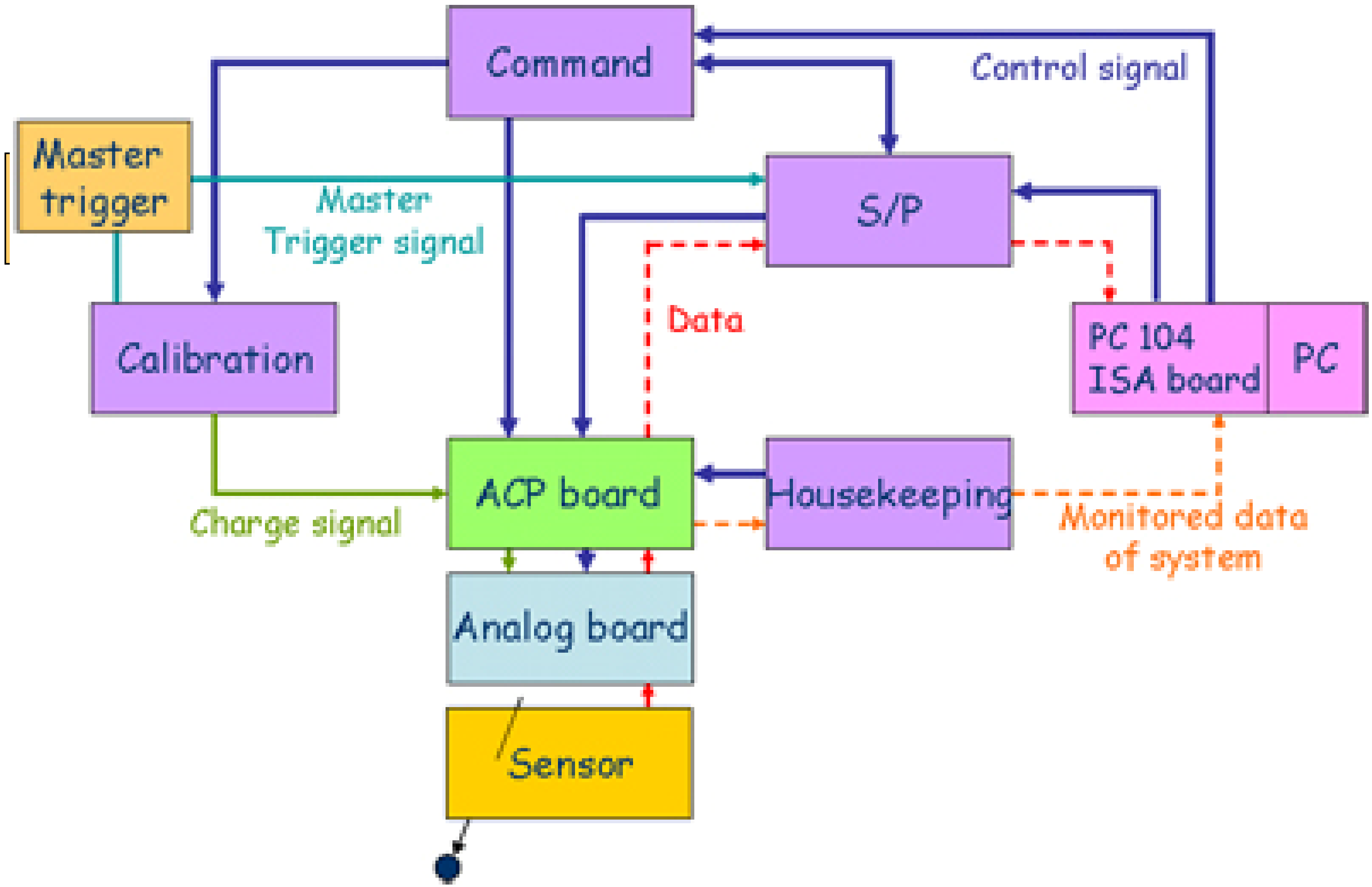
- Custom VLSI (Very Large Scale Integrated circuit) chip
- Developed for large arrays of silicon detectors in the Pamela experiment
- 16 channels of charge inputs
  (integrating the charge pulses -> DC levels)
- Multiplexed to common output line
- Dynamic range : a few fC to about 9 pC with 1 mV/fC Gain,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



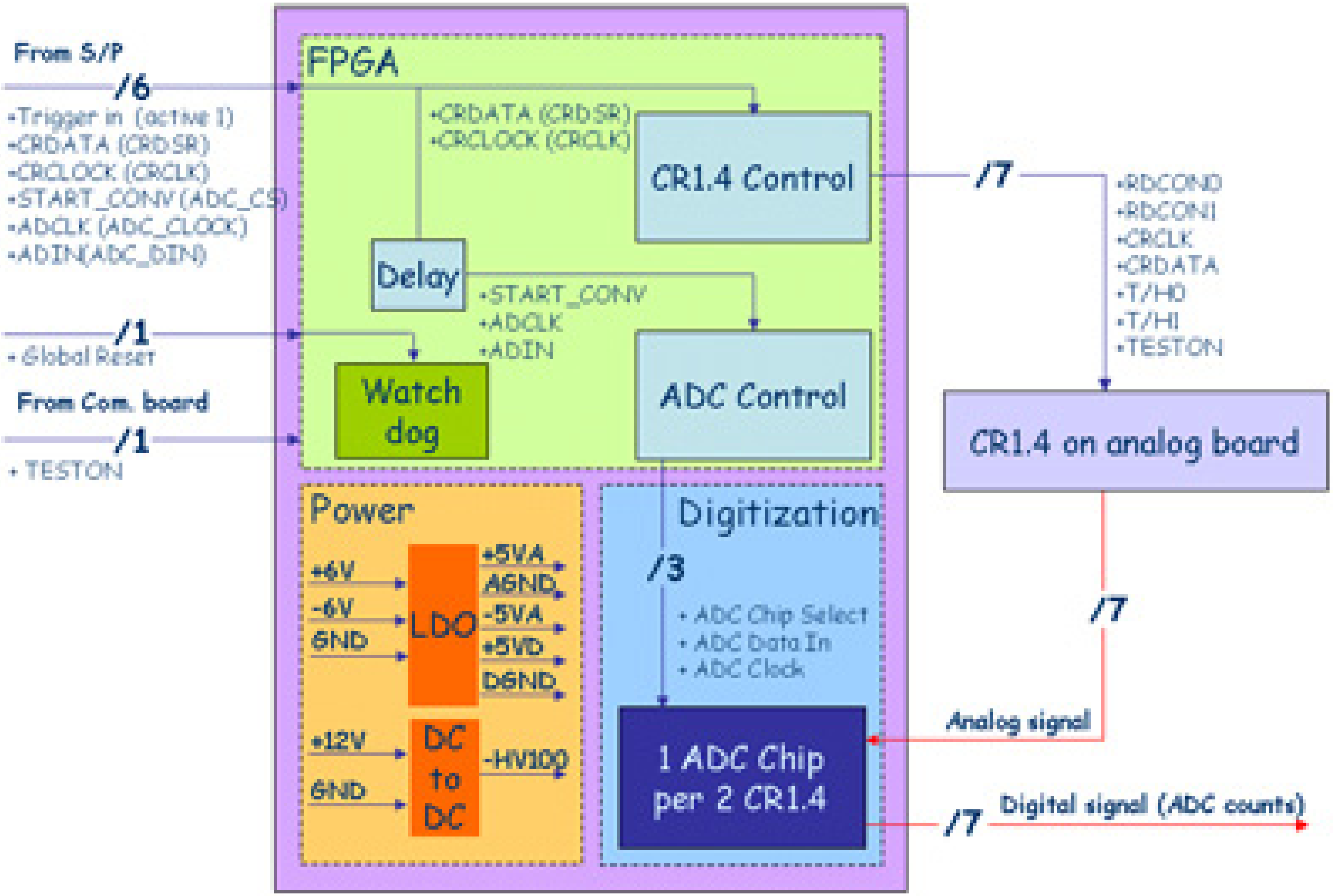


- 1 analog board = 7 CR1.4 * 16 channels = 112 channels

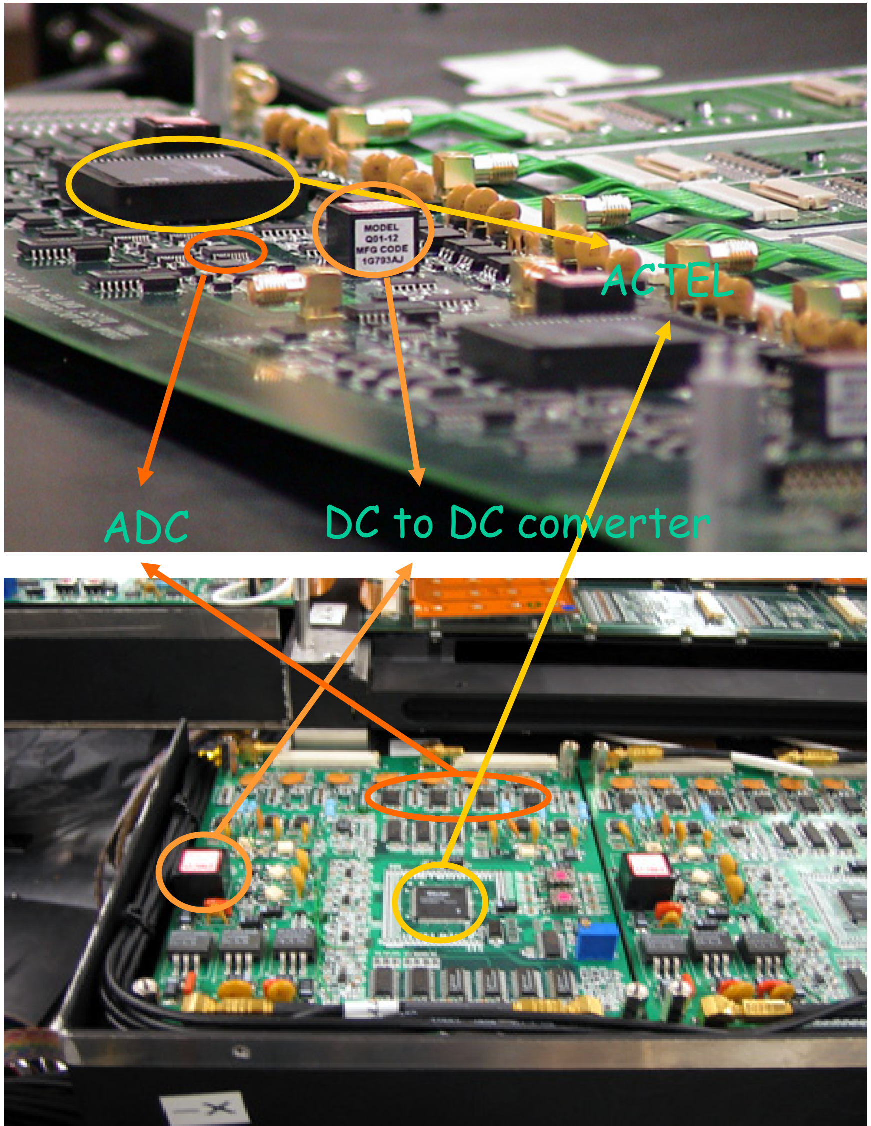
SCD Readout Architecture



Digital Electronics

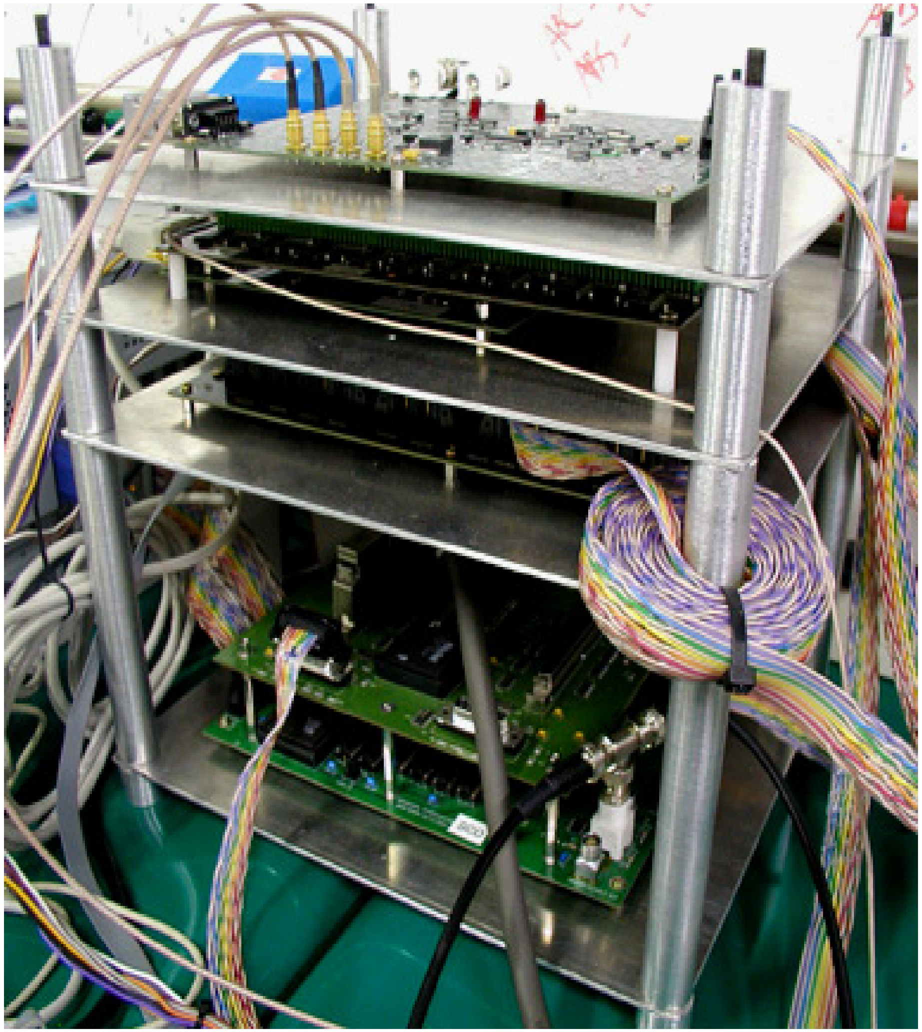


Digital Electronics



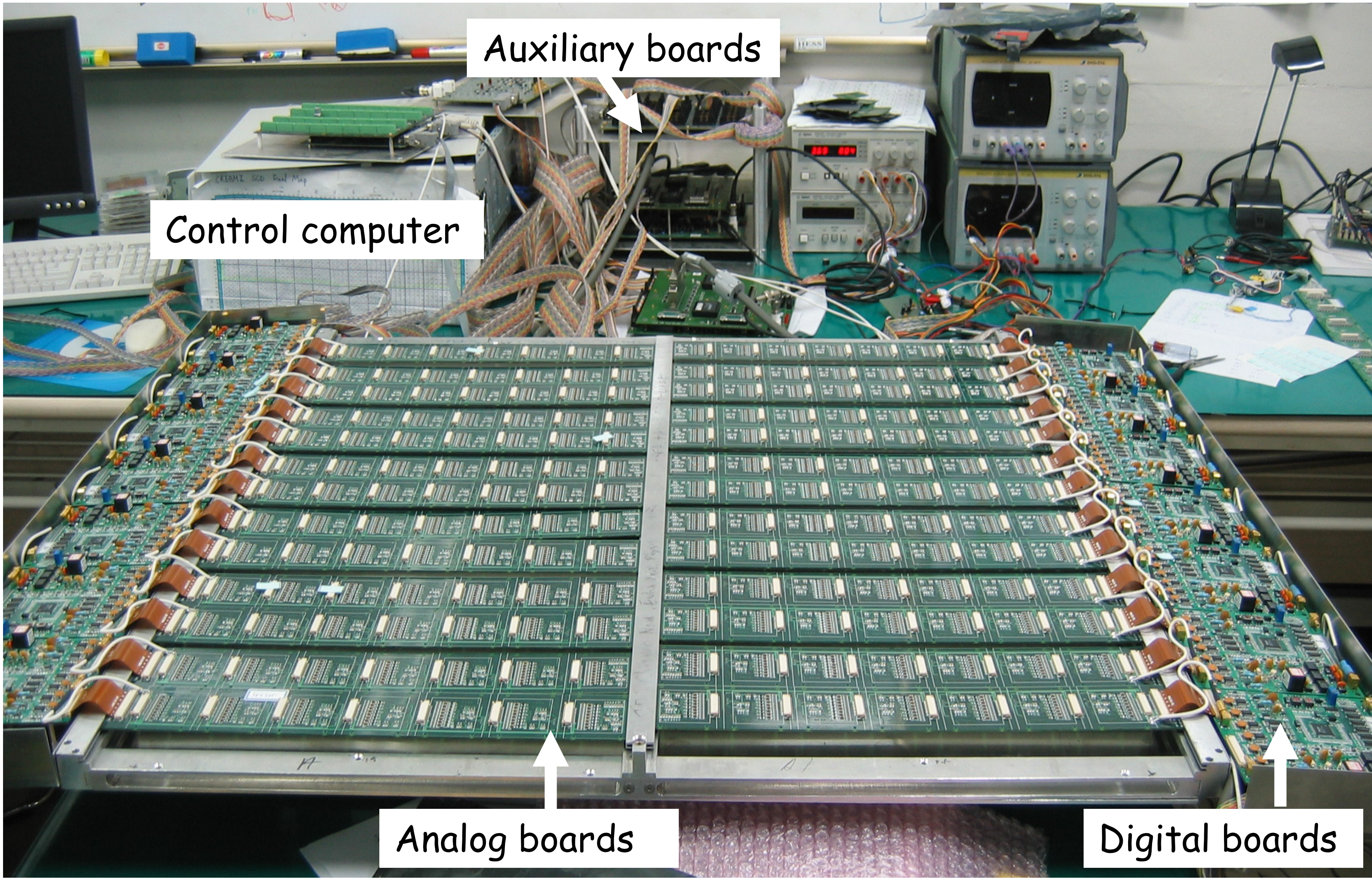
- Digitization : 16-bit ADC MAX1133
  - Temperature range : -40 ~ 85 °C
  - Low power consumption
- FPGA (Control distribution) : ACTEL A42MX
  - Temperature range : -40 ~ 80 °C
  - Low power consumption
- Power (DC to DC converter & Low Drop Out)
  - Q01-12
    - Temperature range : -25 ~ 70 °C
  - LM2990S
  - LX8384, LM1086

Auxiliary electronics

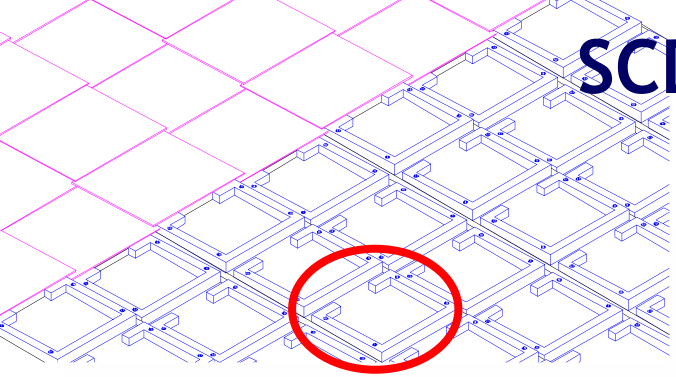


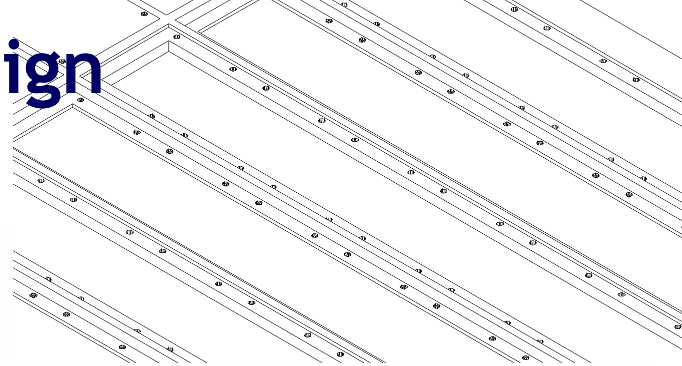
- Calibration board :
  - calibration charge and trigger
- Housekeeping board :
  - Power, temperature monitoring
- Command board :
  - Control command distribution
- Sparsification board :
  - Analog, digital part control clock
  - Data I/O between computer and detector
  - Data sparsificatoin

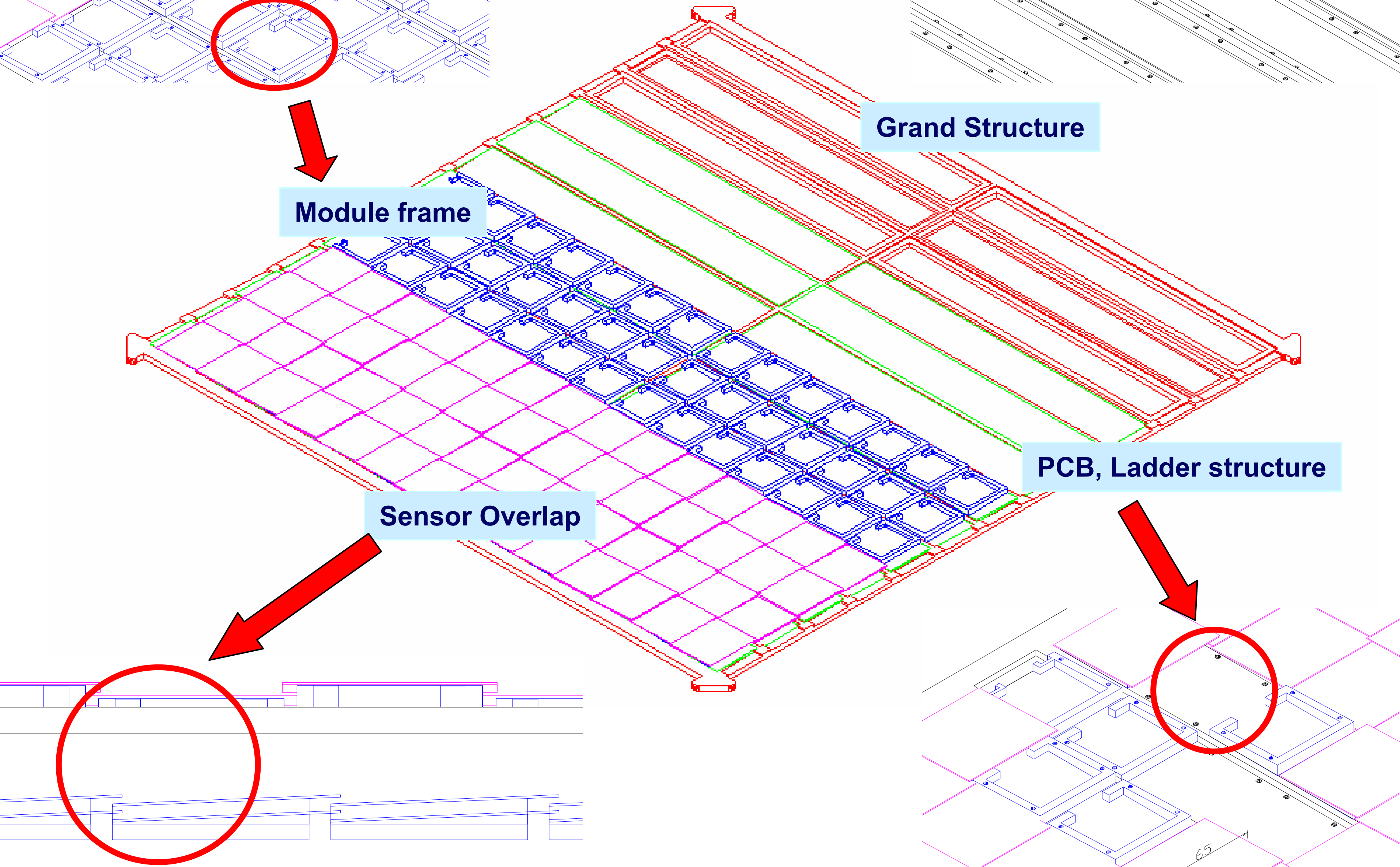
Silicon Charge Detector : Readout electronics



SCD Mechanics Design

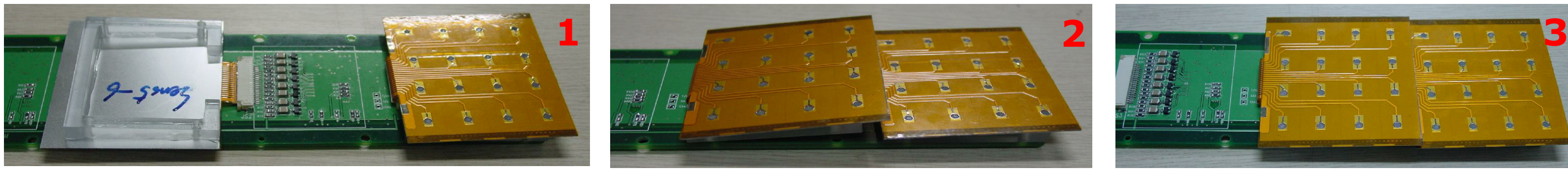




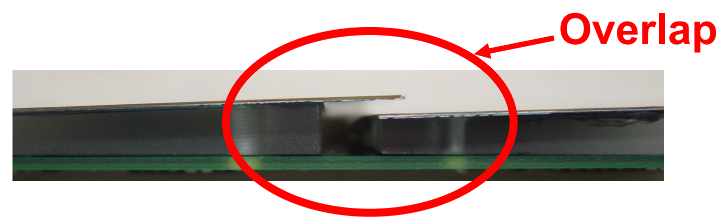


Ladder Assembly

Mount of 7 Sensors on to an electronics board : “detachable design”



A ladder assembled

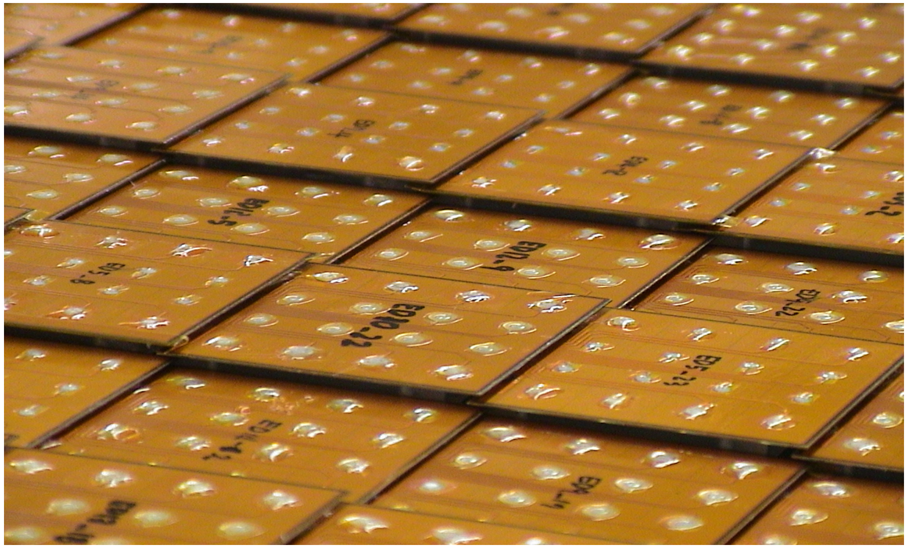


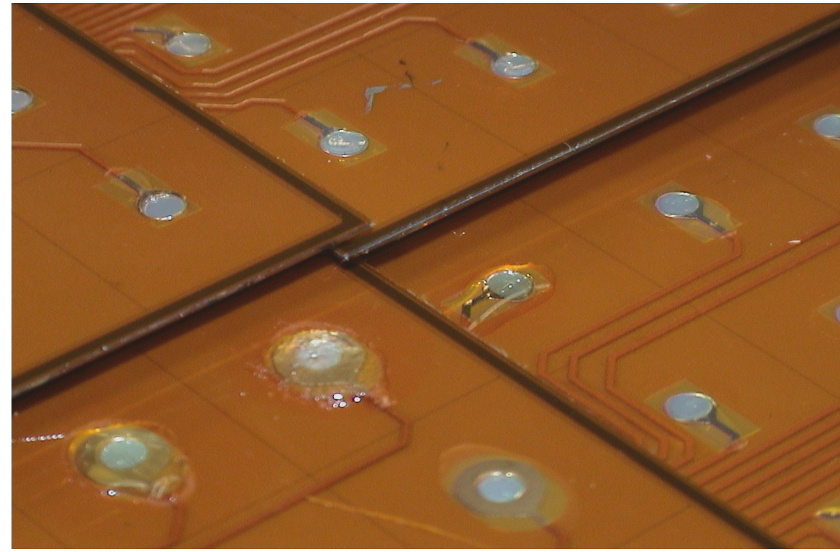
Total 26 ladders in SCD

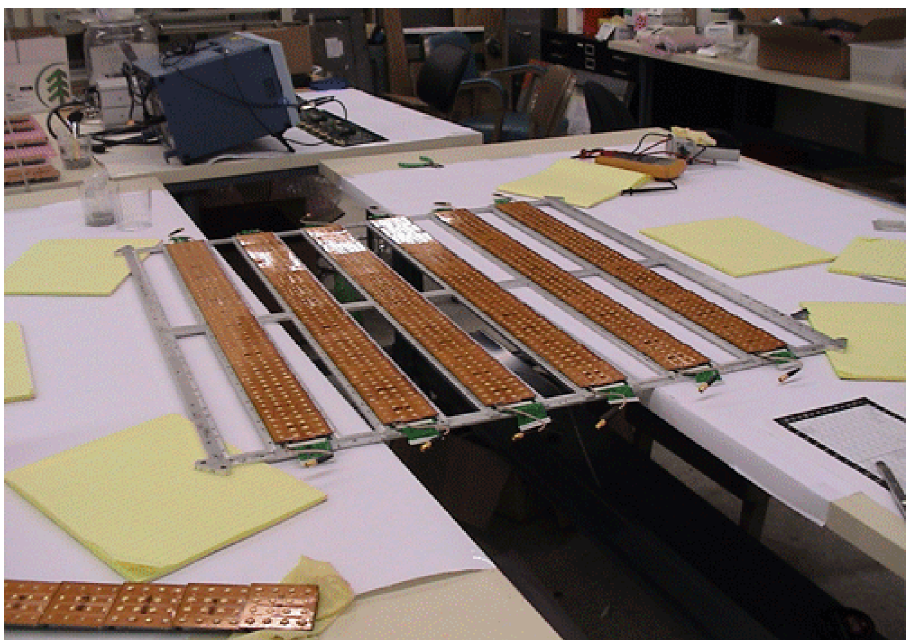
Total 182 silicon sensors

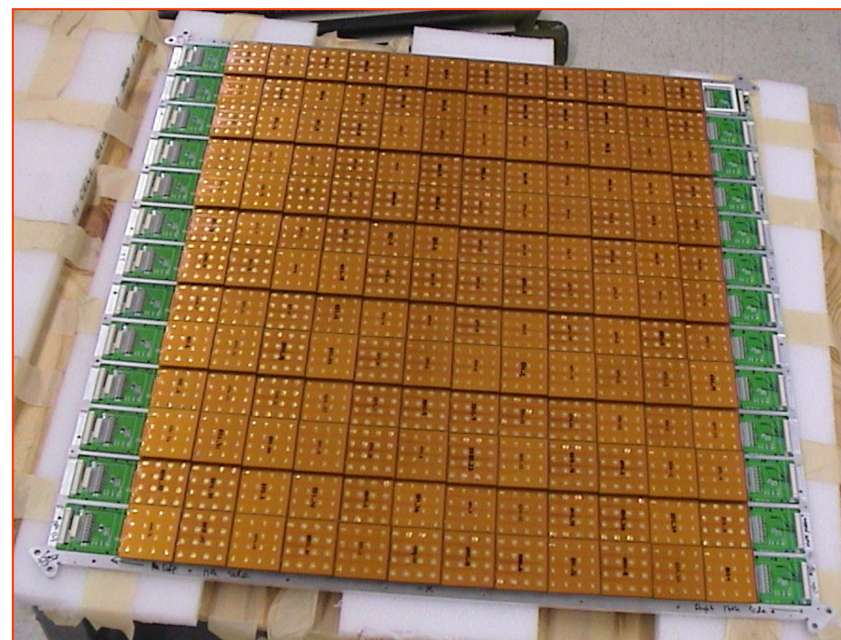
Total 2912 readout channels

SCD Assembly : Ladders on Grand Structure



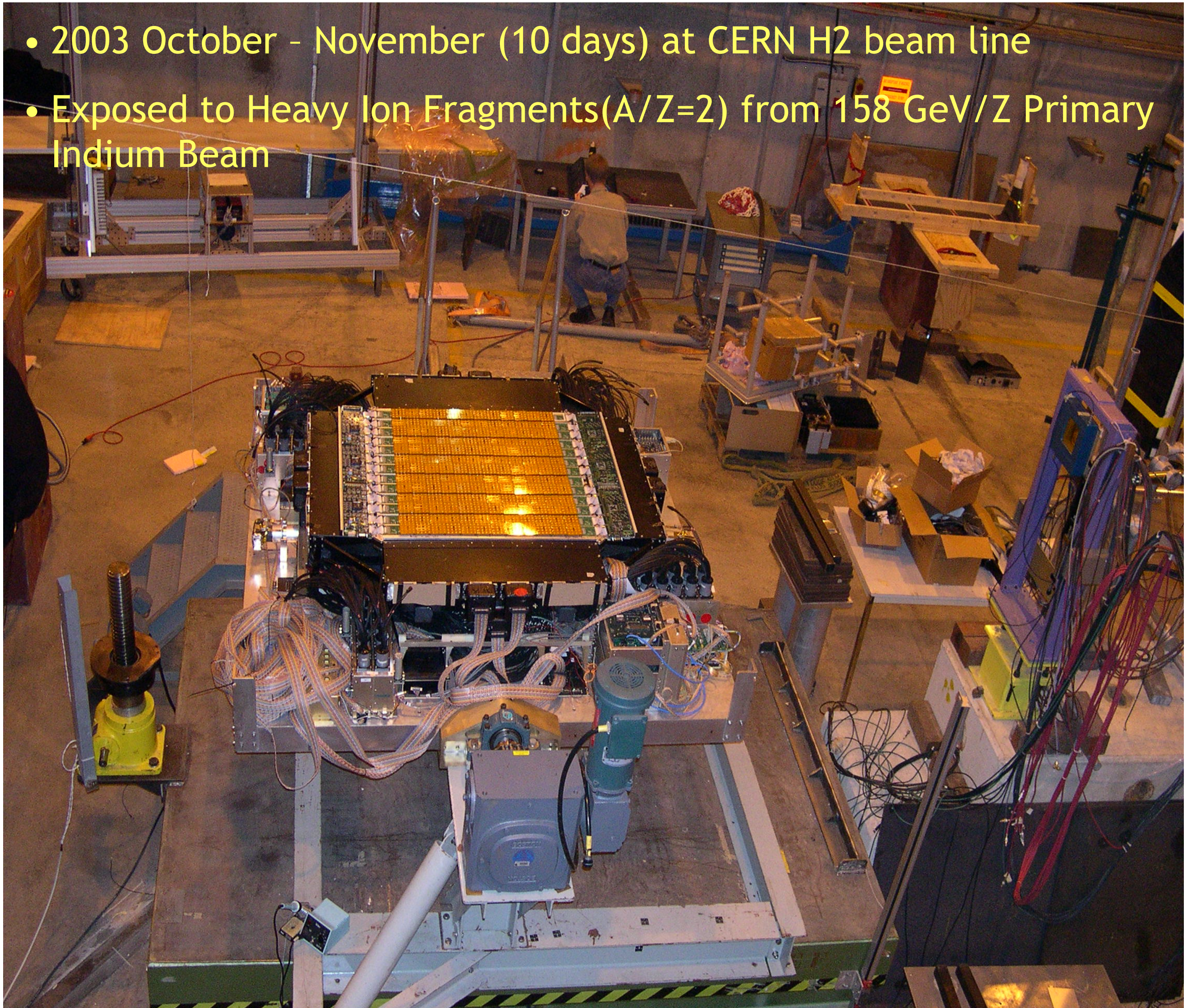






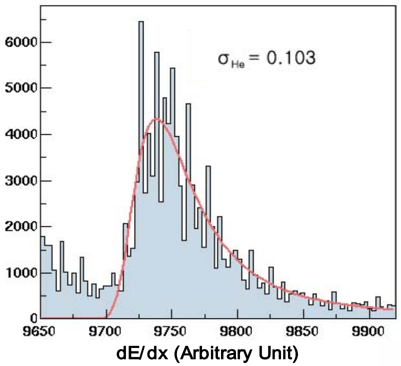
SCD Beam Test — Heavy Ion CERN Beam

- 2003 October – November (10 days) at CERN H2 beam line
- Exposed to Heavy Ion Fragments(A/Z=2) from 158 GeV/Z Primary Indium Beam

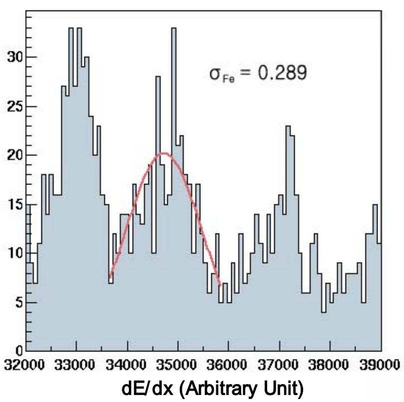


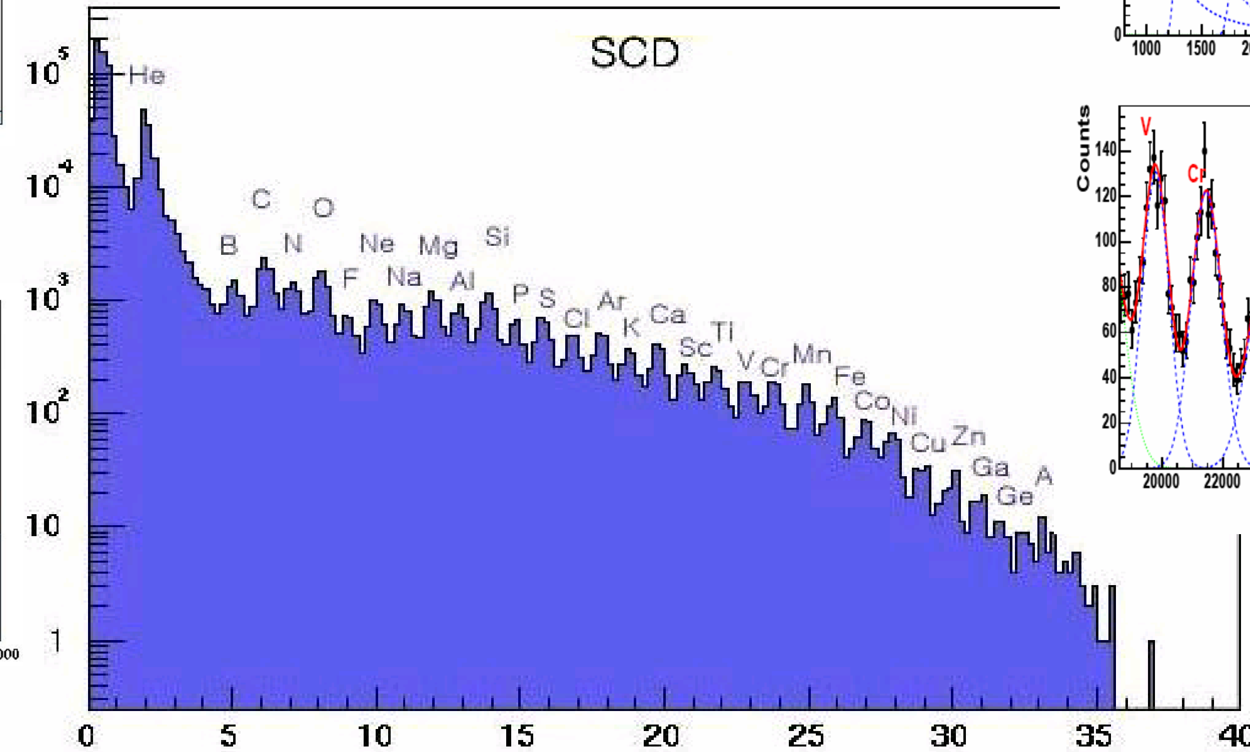
- Charge distribution of beam fragments detected in SCD
- Excellent charge identification up to Z=33

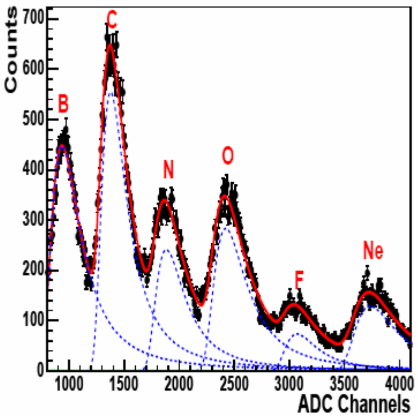
He

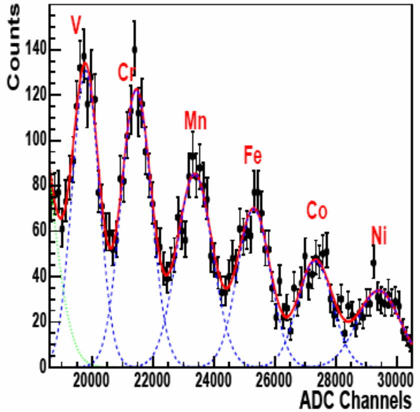


Fe

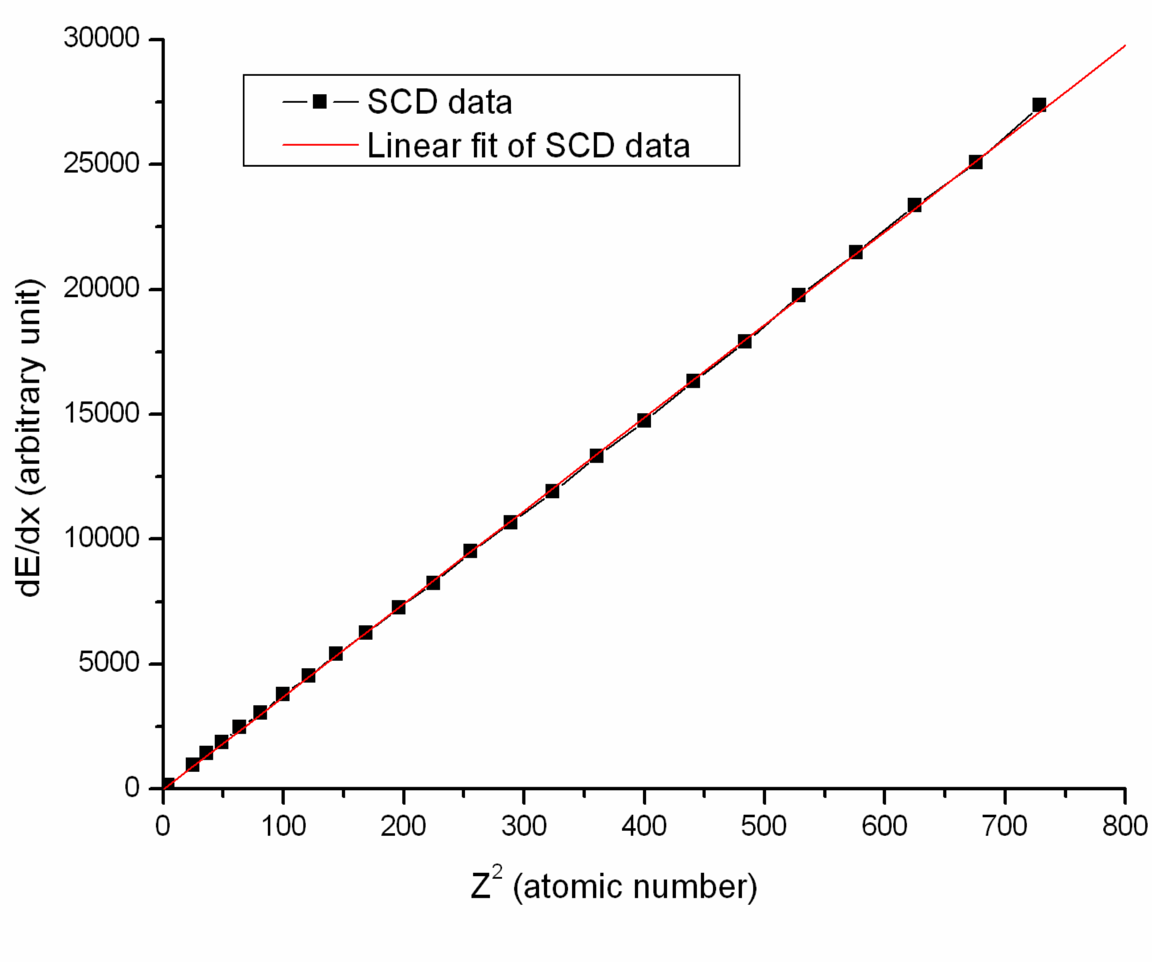






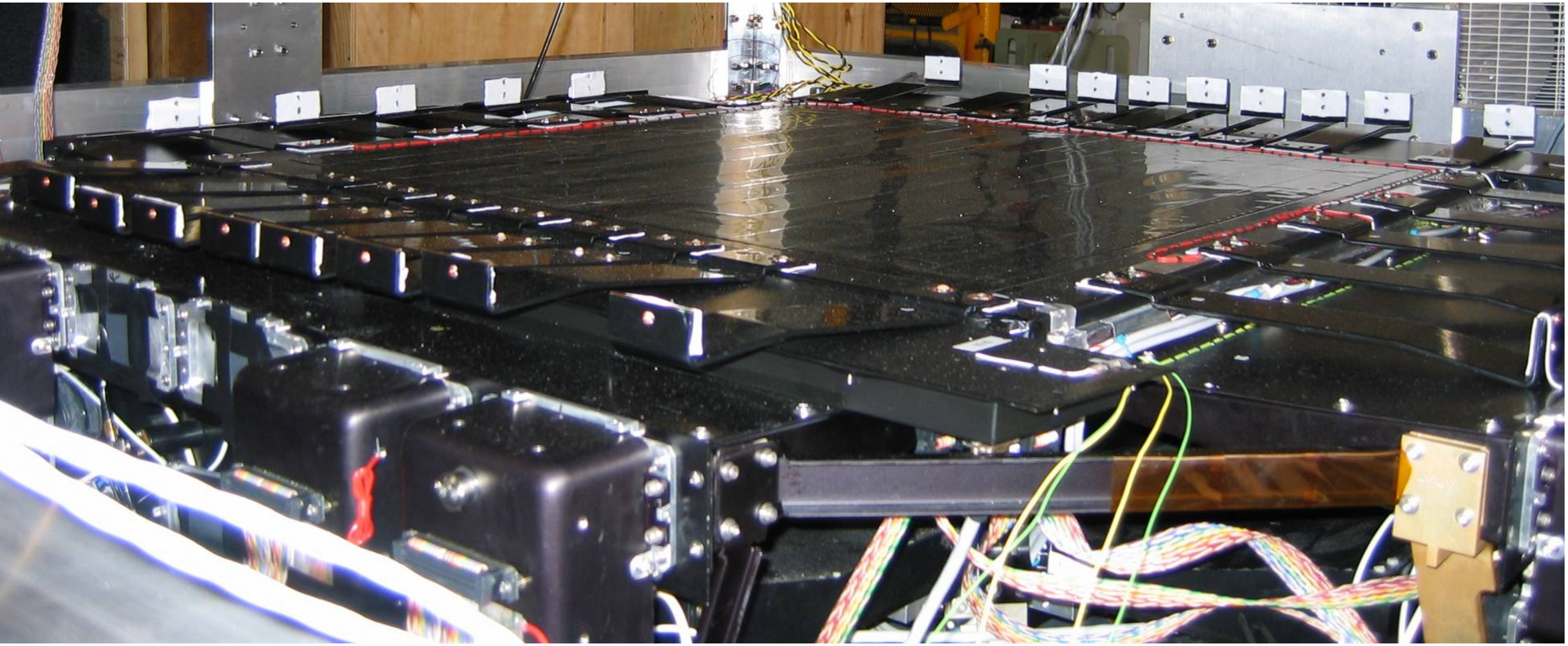


- dE/dx ∝ Z^2
- Linearity in detector gain confirmed over the wide range of Q



Silicon Charge Detector for Space Environment

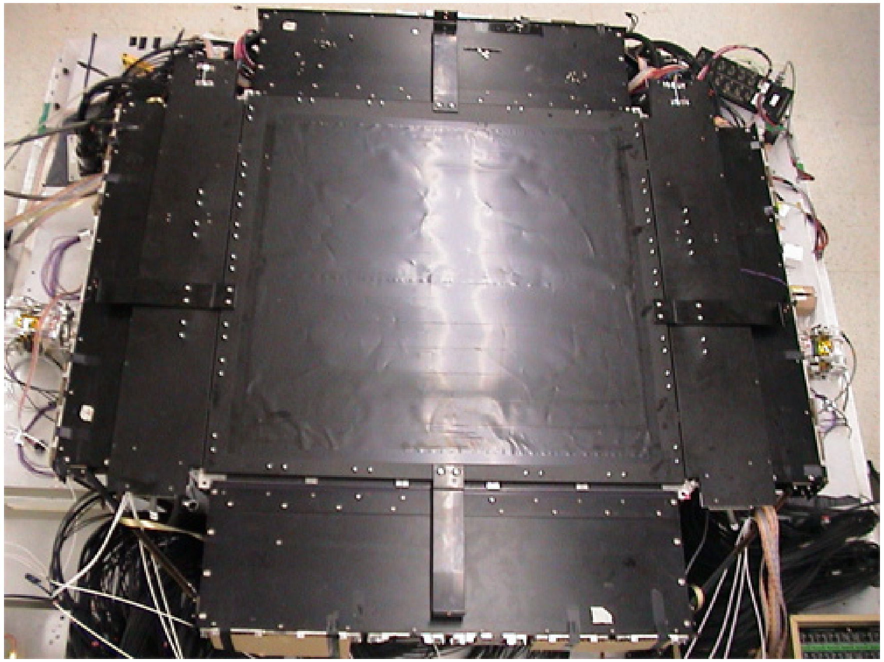
SCD fully assembled for space environment in Aug. 2004



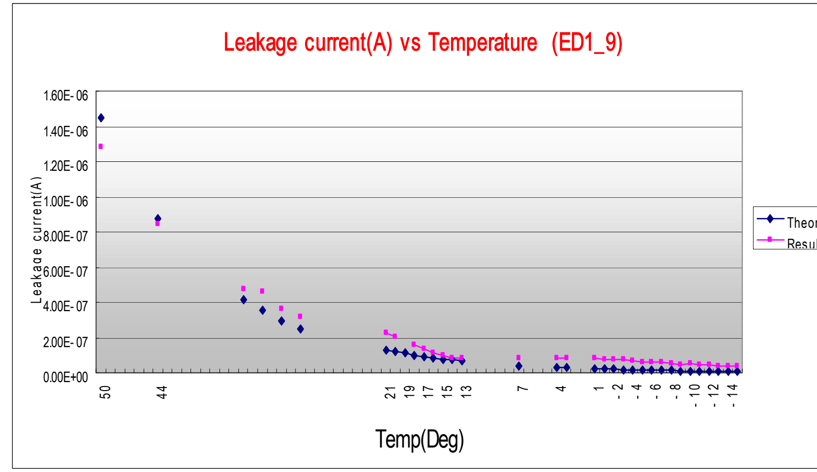
- Preparation for space environment
  - The SCD should be kept within the operating temperature range from balloon environment. On the top of atmosphere, conduction of heat is more prior than convection. To reduce the heat from SCD, used copper strips. Also painted whole detector with black paint to make thermal equilibrium on visual light and infrared range.

Thermal Control

Maintain SCD temperature -10 ~ 40 (‘C) during operation

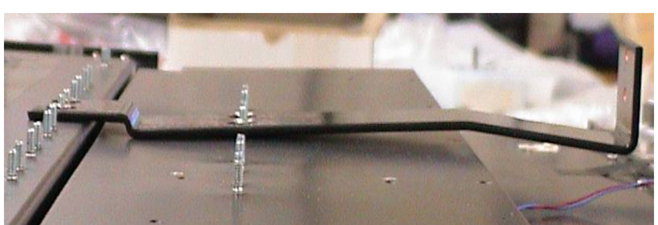


Leakage Current increase at higher temp.

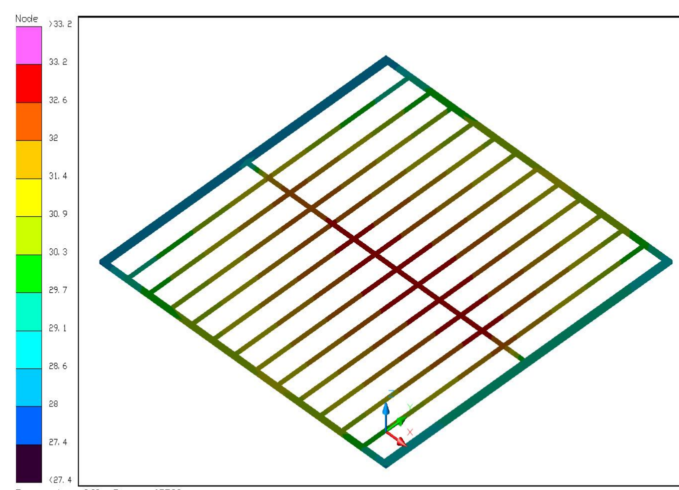


Thermal Strap installed to take heat out,

(air cooling does not work at 5 Torr)

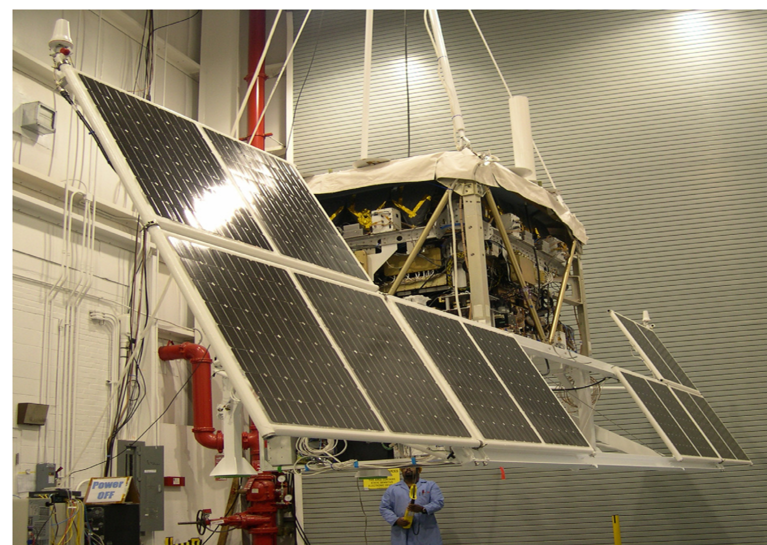


Thermal simulation : SCD is hotter than others



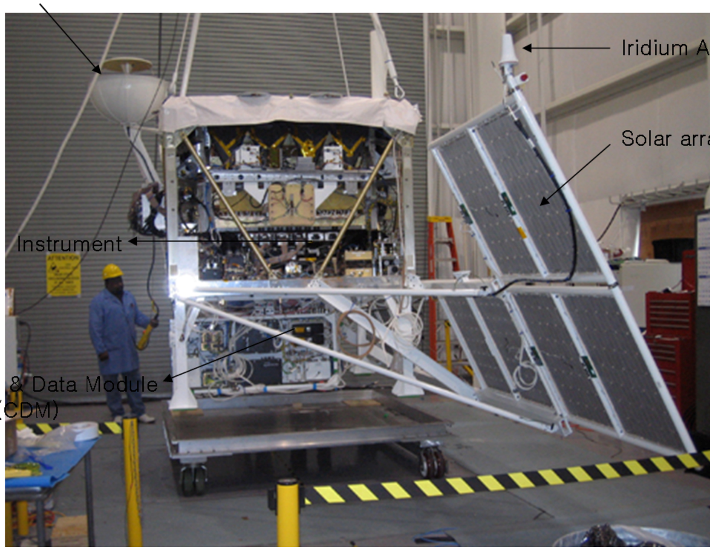
Thermal-Vacuum test at NASA Goddard Space Flight Center

All integated for Thermal-Vacuum test at NASA Gaddard space center

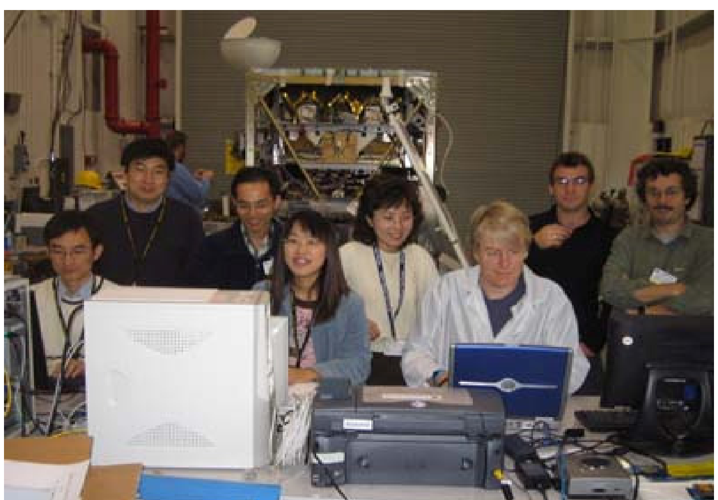


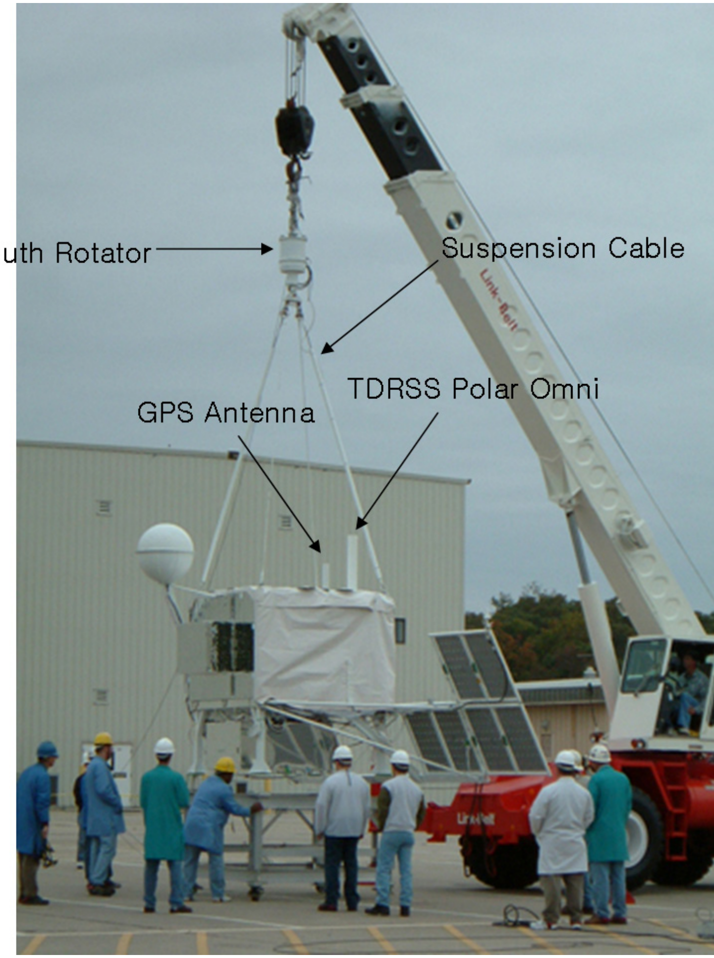
- Environment test at NASA GSFC
  - Test with fully assembled CREAM
  - Temperature : -10°C~40°C
  - Pressure : ~4 Torr
- Hang test at NASA WFF

Final Test at NASA Wallops Flight Facility



- CREAM ballooncraft configuration



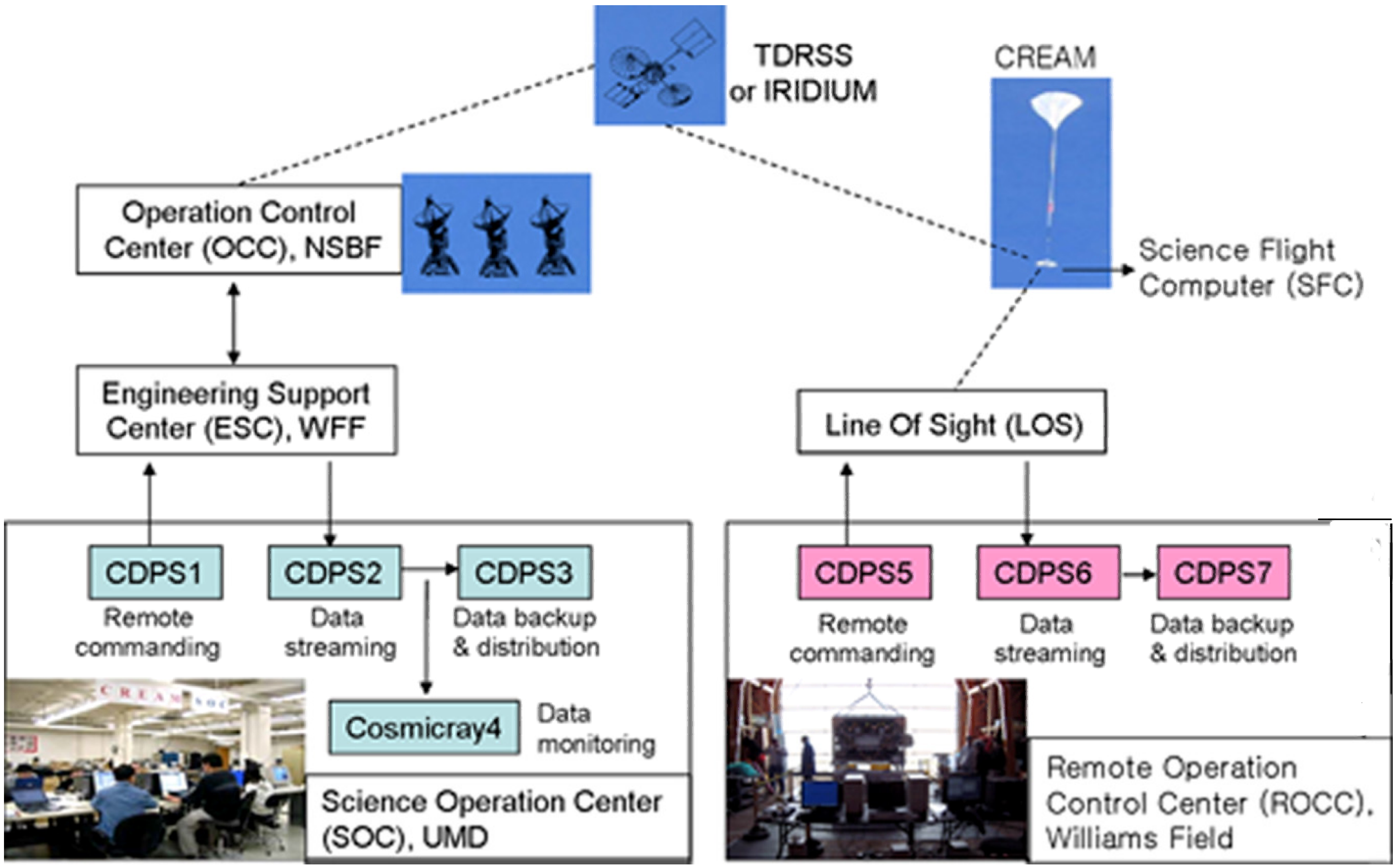


- External Hang Test

CREAM Launch

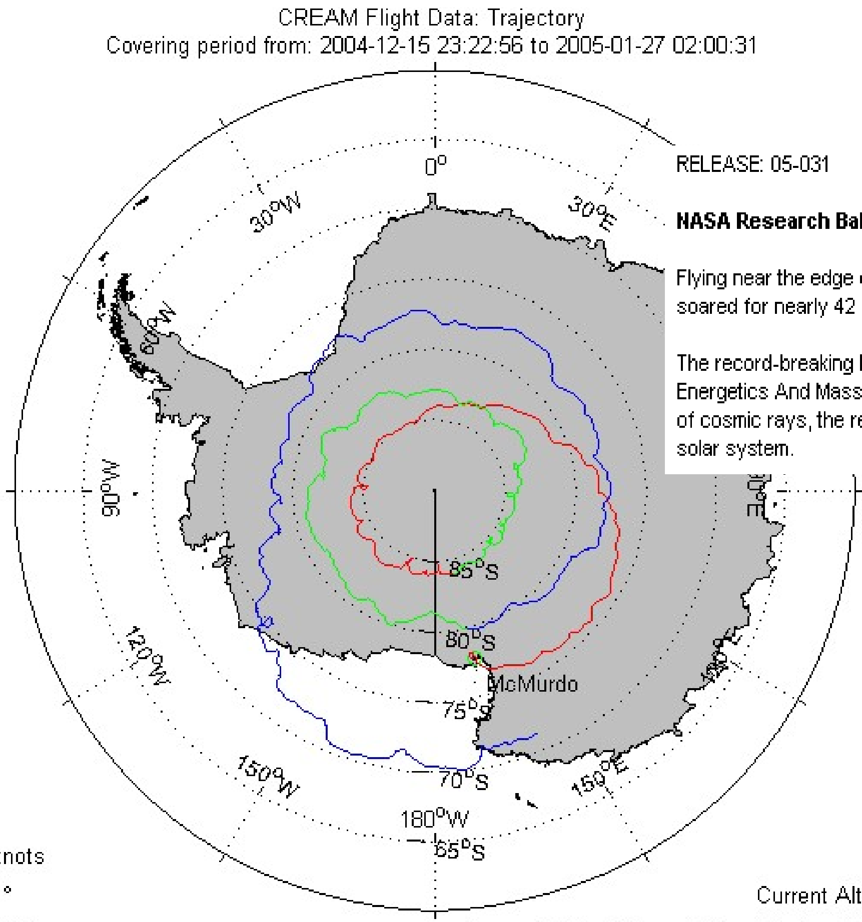
Launch on Dec. 15th , 2004

CREAM Flight Operation



The first flight at Antarctica Dec. 2004

- Flight trajectory
- Total flight time : 41 days 21 hours 31 mins
- CREAM broke both duration and distance records for a long duration balloon flight



NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

RELEASE: 05-031

NASA Research Balloon Makes Record-Breaking Flight

Flying near the edge of space, a NASA scientific balloon broke the flight record for duration and distance. It soared for nearly 42 days, making three orbits around the South Pole.

The record-breaking balloon, almost as large as one and one half football fields, carried the Cosmic Ray Energetics And Mass (CREAM) experiment. CREAM is designed to explore the supernova acceleration limit of cosmic rays, the relativistic gas of protons, electrons and heavy nuclei arriving at Earth from outside the solar system.

Current Speed: 17.2 knots
Current Course: 128.1°
Current Lat: -71°17′3.72″
Current Lon: 157°52′54″

Current Altitude: 13828.7402 feet
Current MET: 41 days 21 hrs 31 mins 30.783 sec since launch
Current Time: 2005-01-27 02:00:31 UTC

CREAM Landing

Landing on Jan. 27th, 2005

Recovered detector may be used for the flight of 2006.12

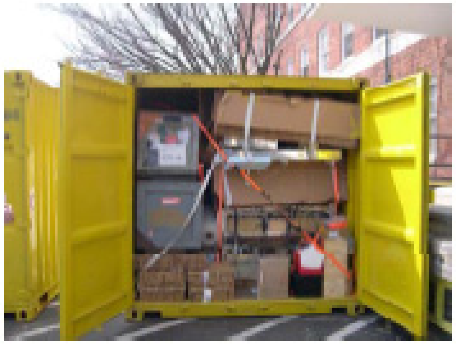
Termination and Recovery of CREAM

CREAM parachuting down after termination

CREAM after landing on the ICE

The recovery mission using a Twin Otter plane

Impact Location: 417 Nautical Miles (27,660km) north northwest of McMurdo Station
Impact Date: 27 January 2005



Instruments came back to UMD in good shape. (2005/04/01)

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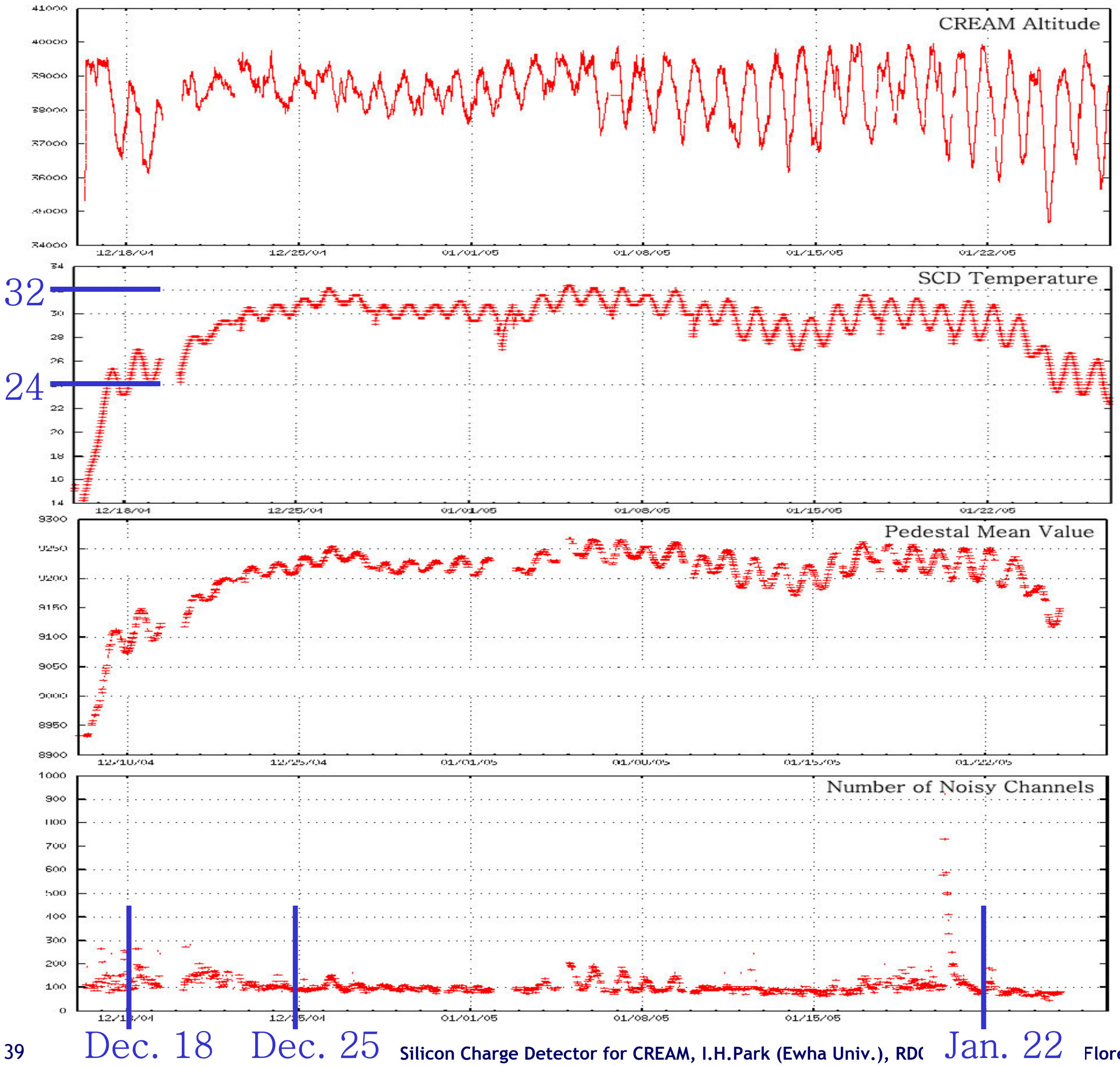
SCD Performance during the Flight



CREAM Altitude

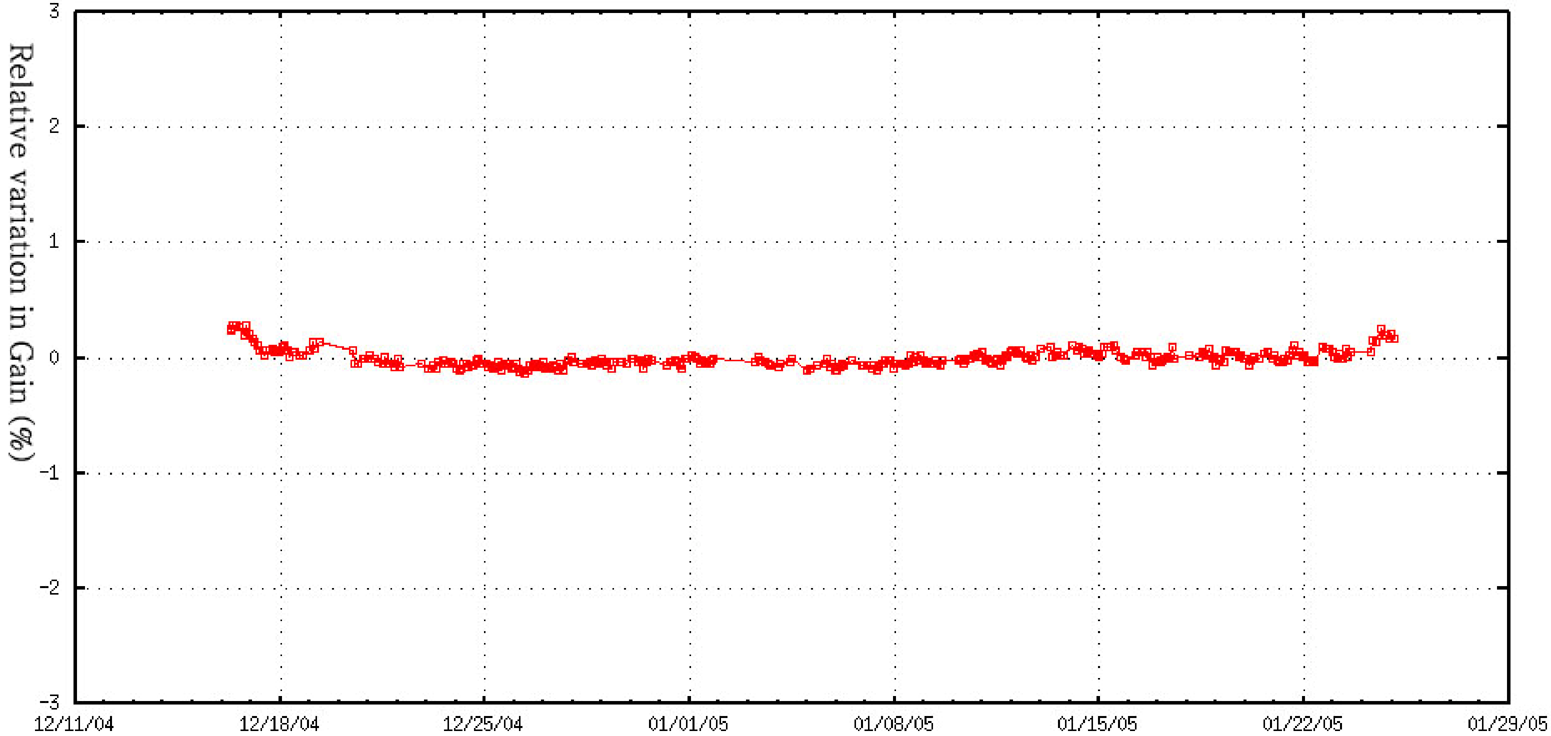
Temperature of Frontend Readout Boards

Pedestal Mean Value

Number of Noisy Channels
~ 3% in average
(out of 2912 ch.)

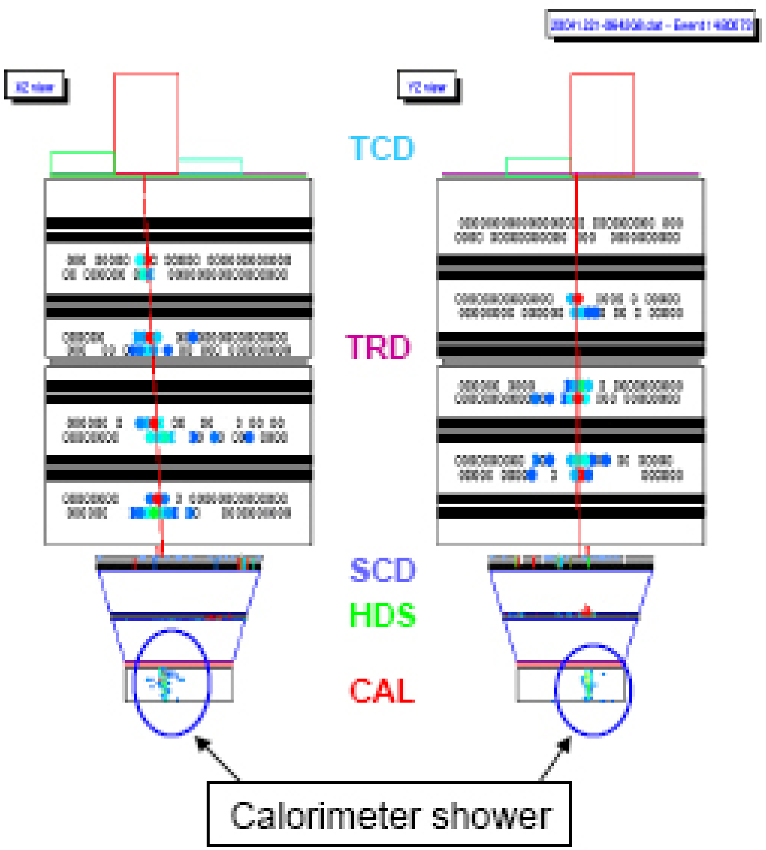
Electronics Gain Calibration

Electronics calibration was made periodically during the flight
by injecting a fixed amount of charge

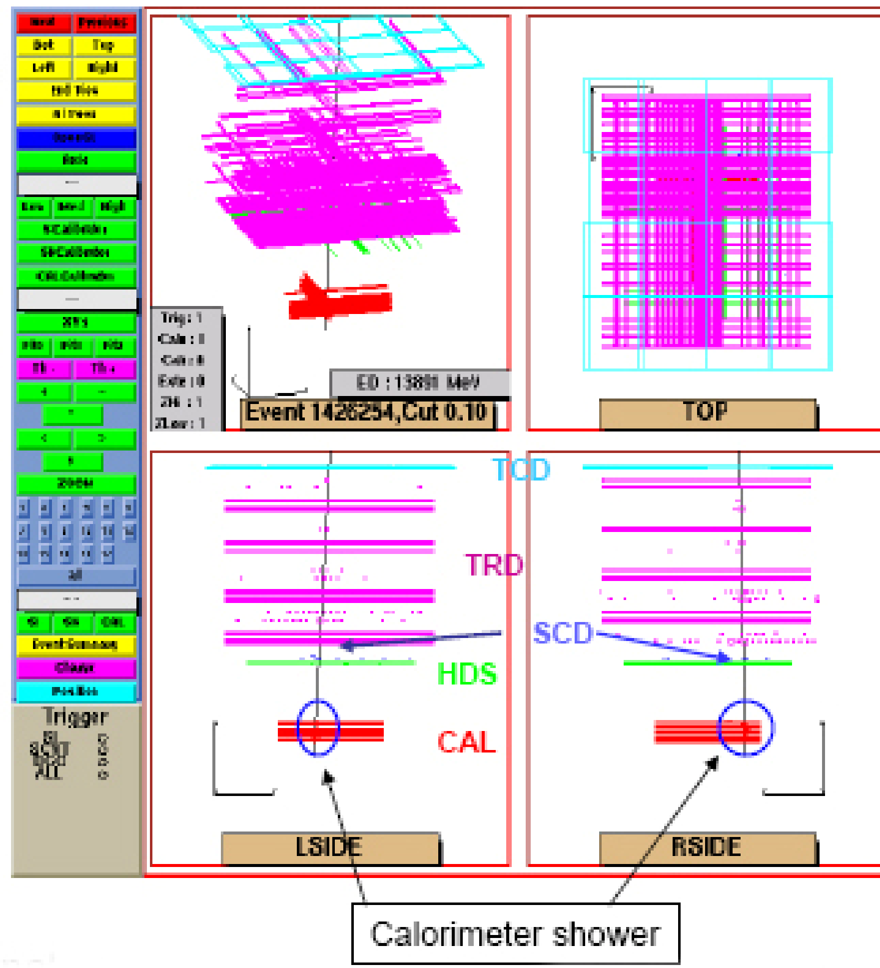


CREAM Event Display

- CREAM Monitoring program (CMon)



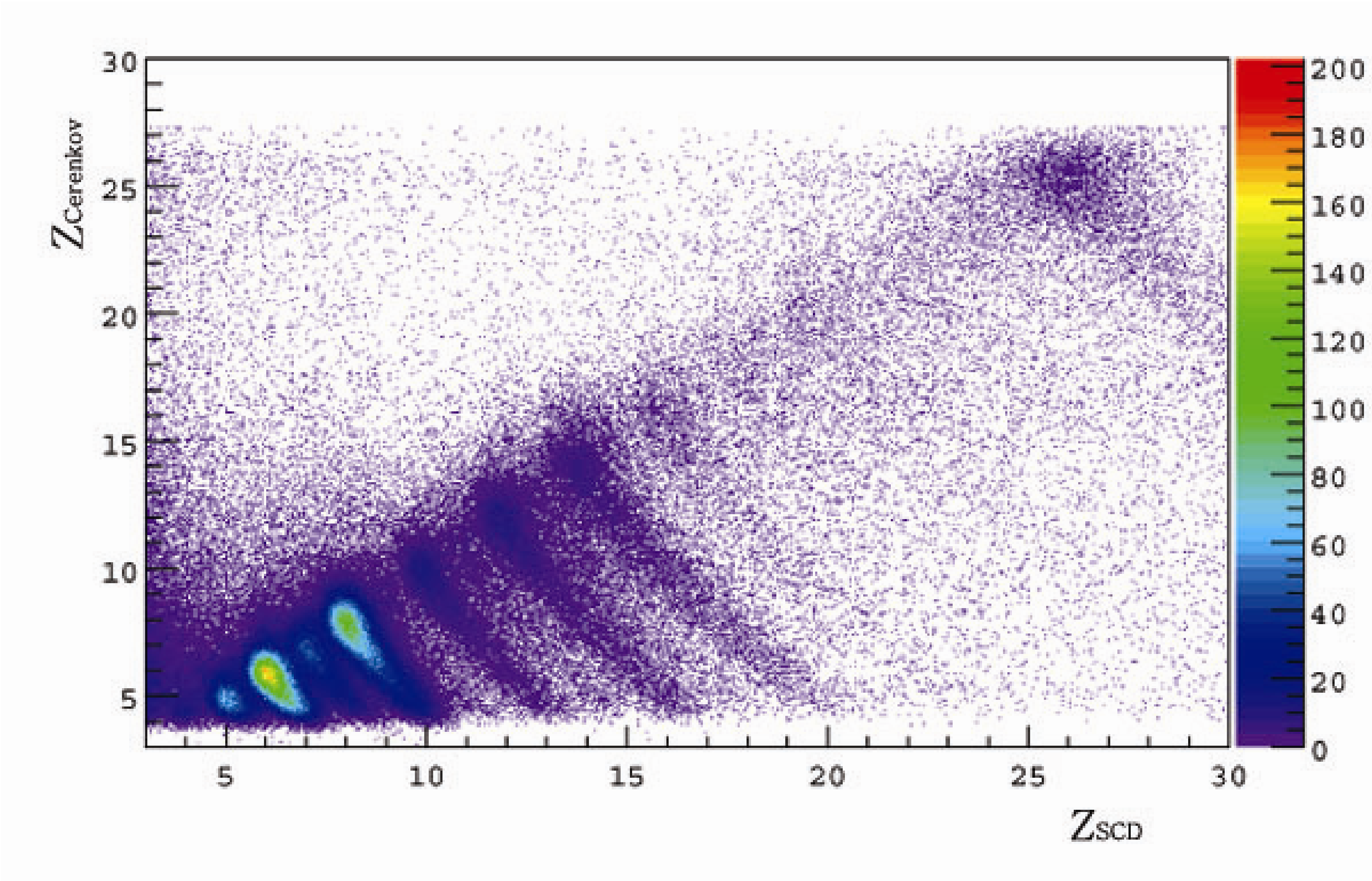
- CREAM Data Processing System (CDPS)



- An example event : ~ 10 TeV Fe candidate

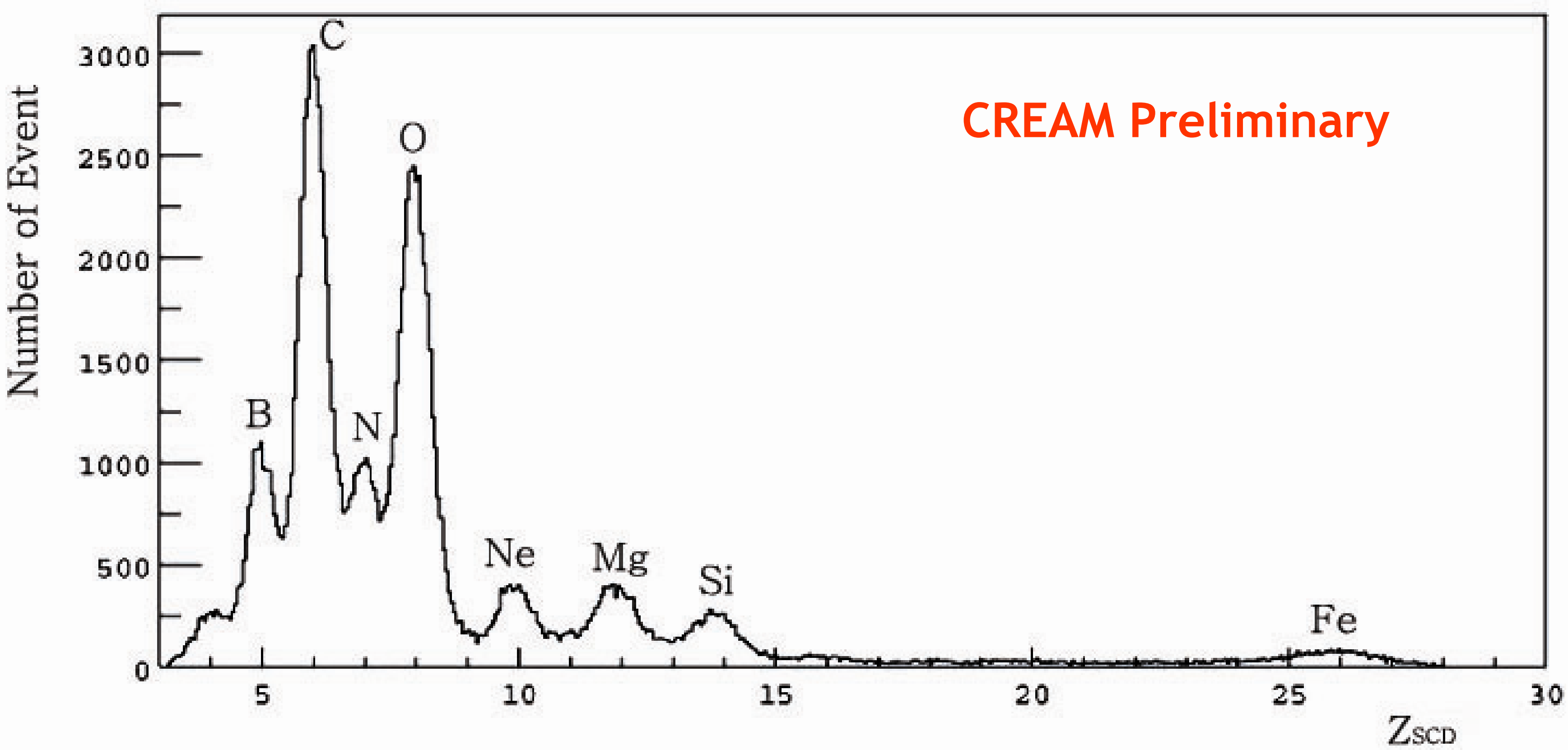
Correlation Between SCD and Cherenkov Counter

Correlation between SCD signals found in the area near the TRD track intersection and signal of Cherenkov Veto Counter.



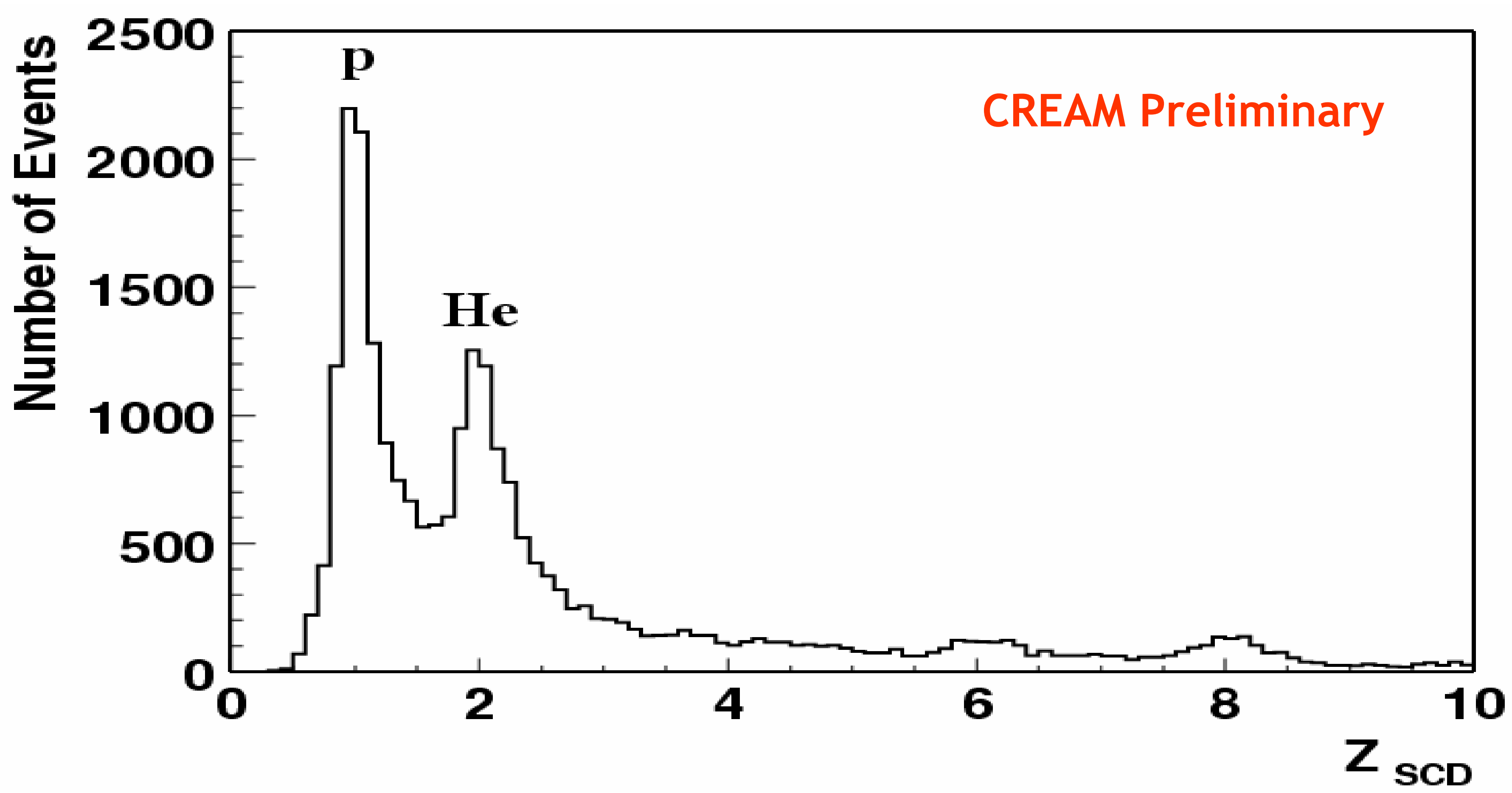
Charge Spectrum (High-Z Region)

SCD Charge spectrum by the projection of high energy signal.
The relative abundance was not corrected here.



High Energy Cosmic Ray Charge Spectrum

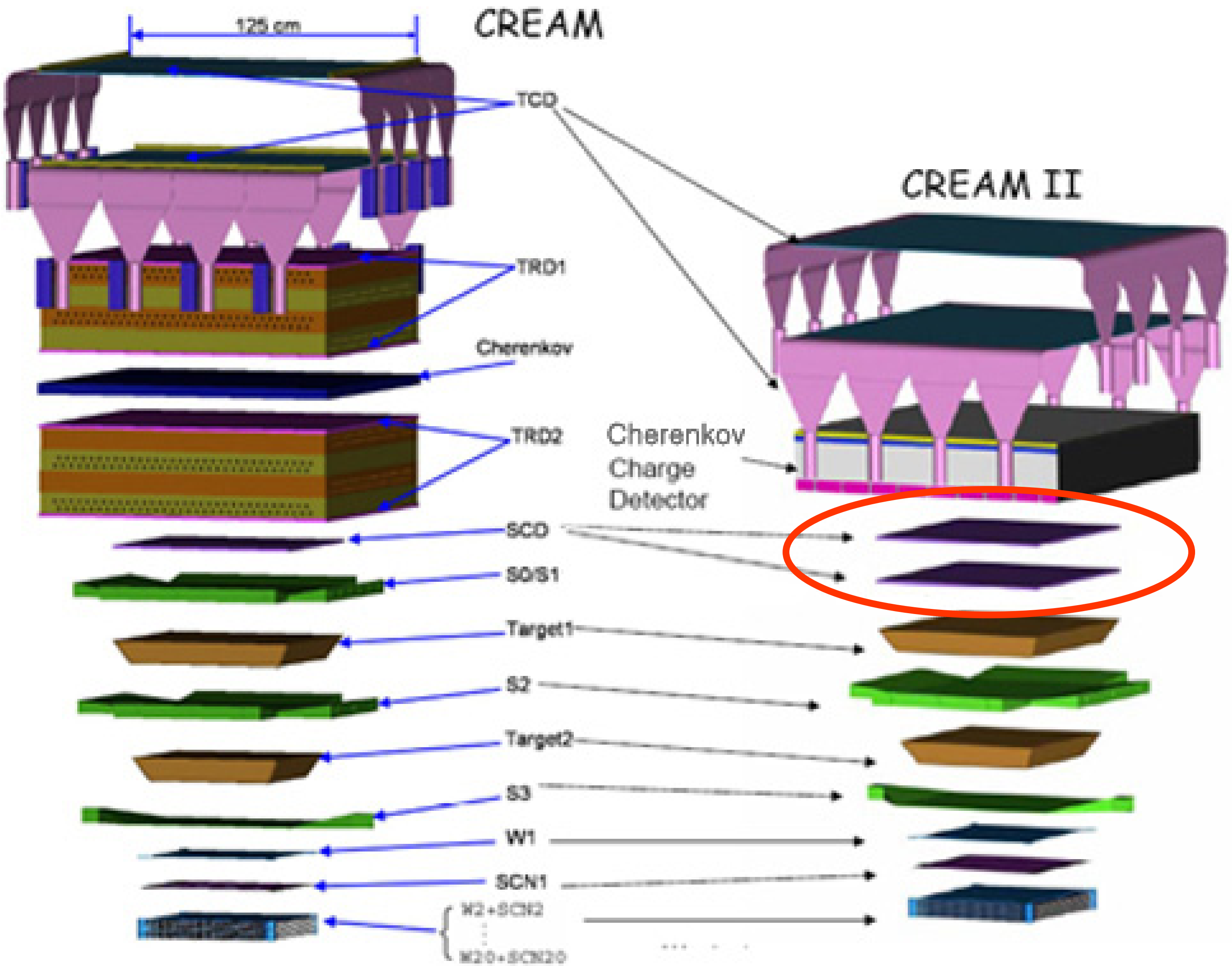
Events triggered by Calorimeter High Energy Threshold
The relative abundance was not corrected here.



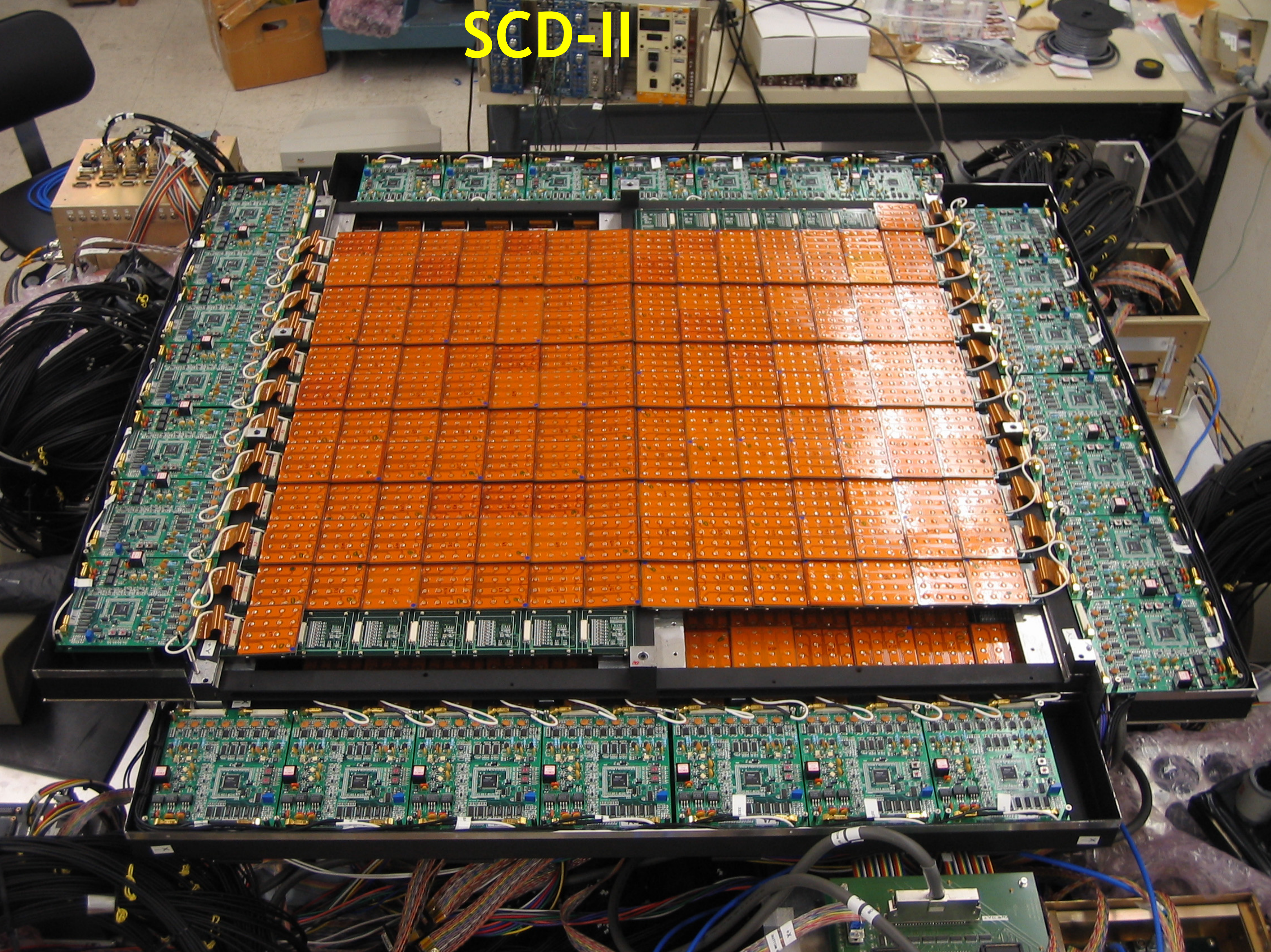
Summary

- The aim of the CREAM(Cosmic Ray Energetics And Mass) experiment is to understand the source and acceleration mechanisms of very high energy cosmic-ray particles.
- The Silicon Charge Detector (SCD) was built for charge identification of incident cosmic rays.
- CERN Beam tests showed charge resolution better than 0.2 charge unit, as designed
- The CREAM payload was launched successfully in December 2004 from McMurdo Station, Antarctica as a Long Duration Balloon mission.
- SCD operated well on the first flight of 2004-2005 and measured the charge of cosmic rays without any problems
- SCD-II is being ready for 2005-2006 flight

CREAM-II for Dec. 2005 Flight



Double layer of Silicon


SCD-II