Highlights of particle physics

- Tracking in particle physics experiments
- Challenges for the Sensors
  - Speed
  - Granularity
  - Radiation hardness
- Status of the R&D
  - From a Liverpool perspective

High energy physics experiments

- Tracking in essentially measuring the path of minimum ionising particles
- Very high multiplicity
- High repetition rate (the present interaction frequency at the LHC at CERN is 40MHz)

High energy physics experiments

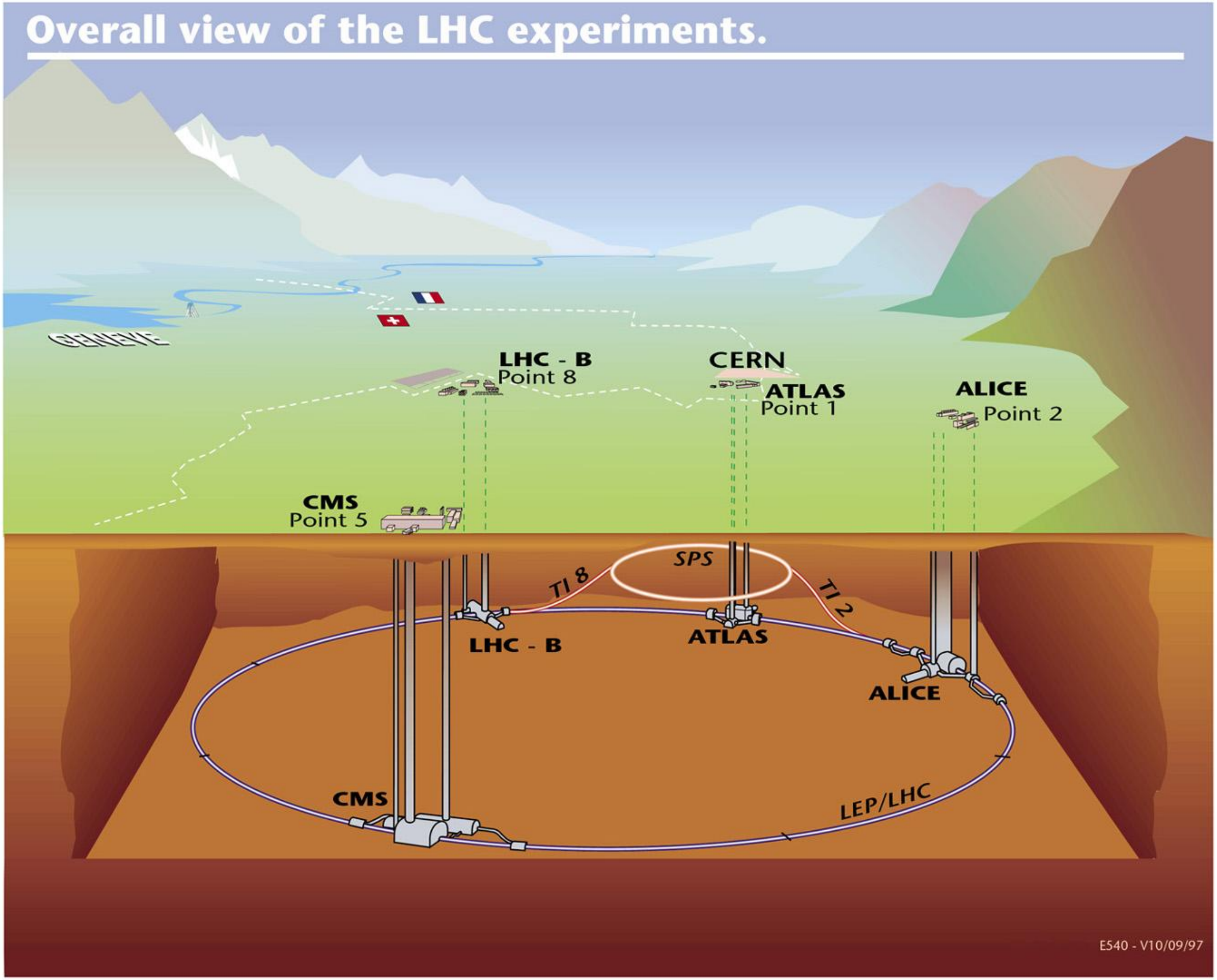
The Large Hadron Collider under the French-Swiss border near Geneva

High energy physics experiments

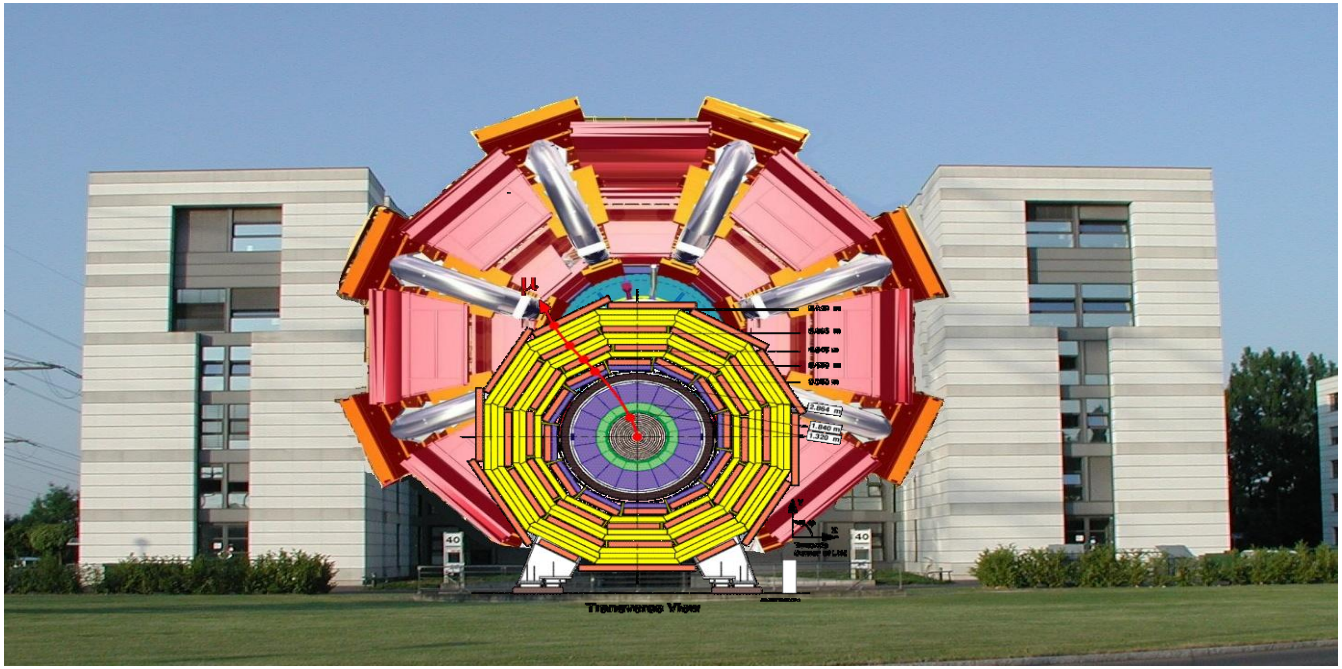
HEP Experiments are big!

1232 superconducting (1.9 K) dipoles are needed to bend the beams around the 27 km circumference of the LHC.
At 7 TeV these magnets have to produce a vertical B field of 8.4 Tesla at a current of 11,700 A to bend the beam round via the Lorentz force.
The magnets have two apertures, one for each of the counter-rotating beams.
Each one is 14.3 metres long, weighs 35 tonnes and costs 0.5M€
Quads etc are also needed to keep the beam focused and the motion stable
The total stored magnetic energy in the LHC is 11,000,000,000 Joules
With 2808 bunches in the LHC, the stored kinetic energy in the beam is 350,000,000 Joules

High energy physics experiments

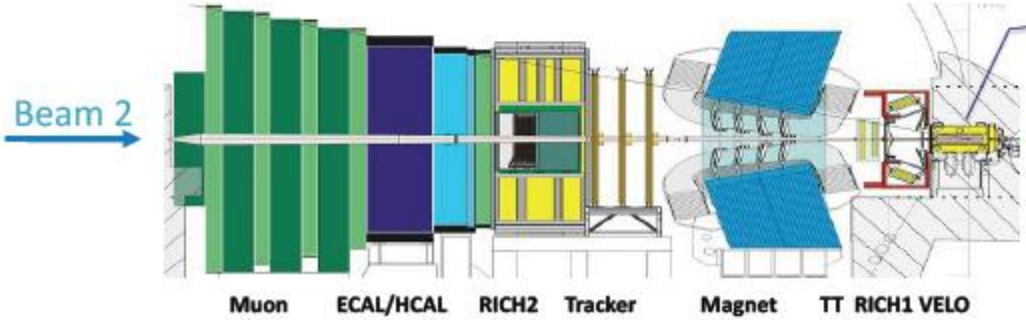


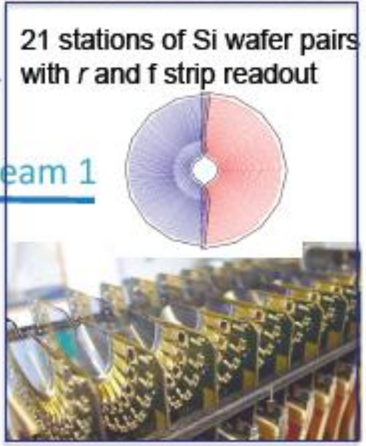
High energy physics experiments



- **ATLAS, CMS, ALICE and LHCb**
- **Detector Technologies**
  - **Noble gases, scintillators, crystals, Cherenkov, …**
  - **Silicon Micro-strip Tracking Detectors**

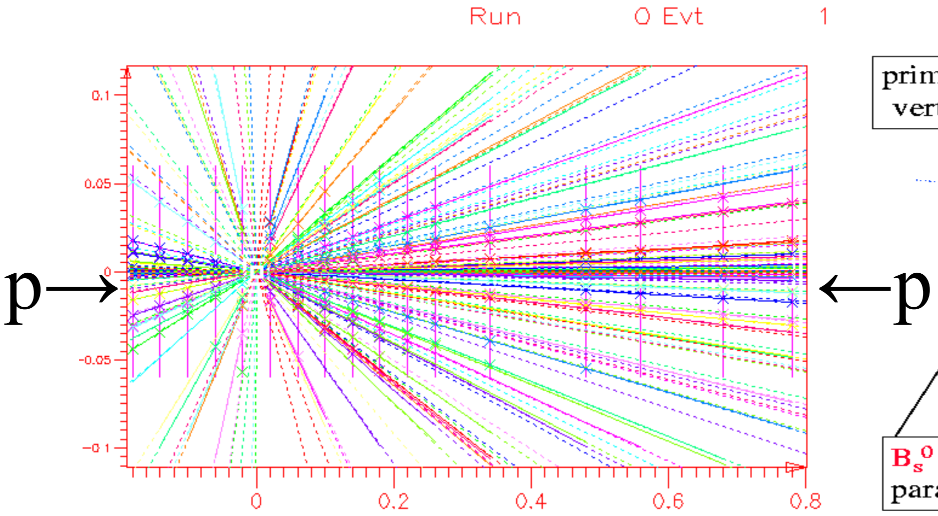
The LHCb experiment



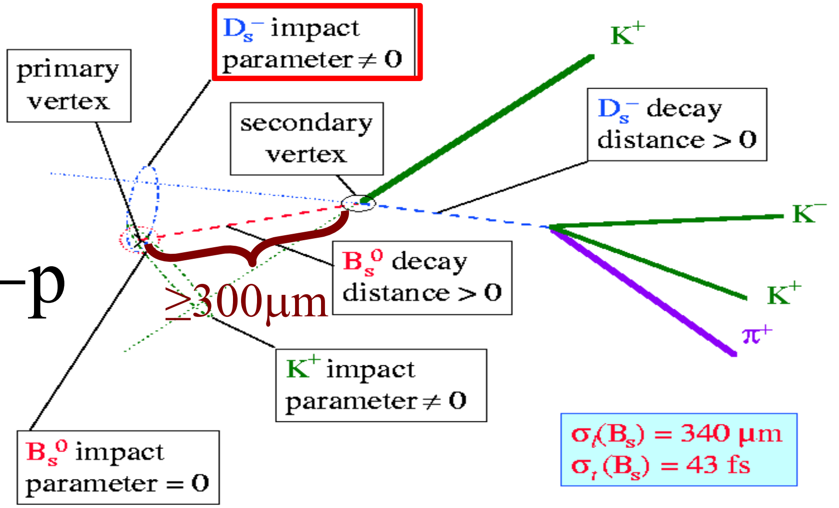

21 stations of Si wafer pairs with *r* and f strip readout

High energy physics experiments

- Nearly all early applications of silicon micro-strip detectors were to detect and measure particles with pico-second (10^{-12}) lifetimes such that (taking account of special relativity) $\beta\gamma c\tau \geq 300\mu m$
- This meant the primary goal was to locate primary (collision) and secondary vertices (as is the case in LHCb)



Side on view of 7 TeV on 7 TeV proton collision



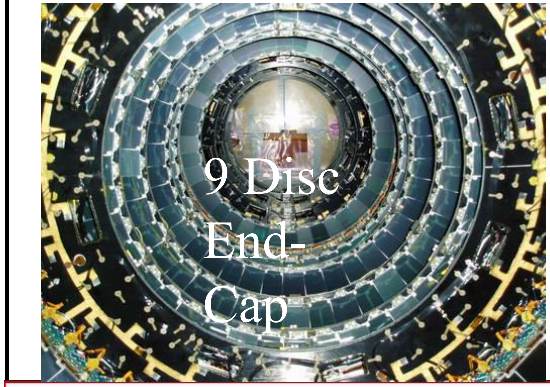
Zoom in showing just particles from B_S-meson decay

The LHCb-VeLo detector

All built in the Liverpool Semiconductor Detector Centre!

The ATLAS experiment

Liverpool and NIKHEF



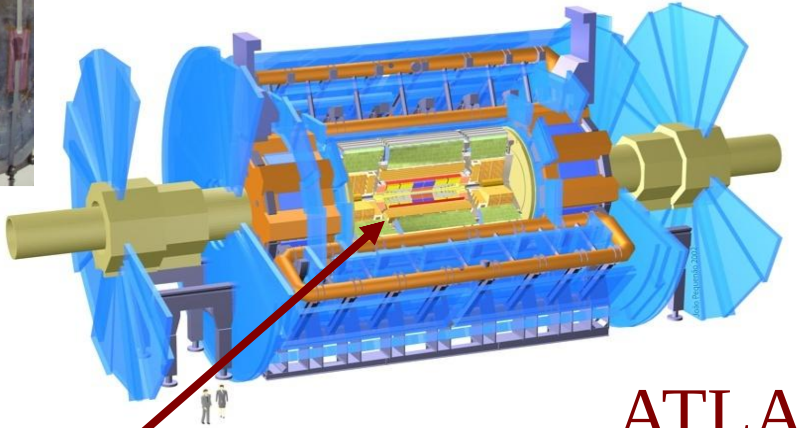
9 Disc End-Cap

2 End-Cap Arrays

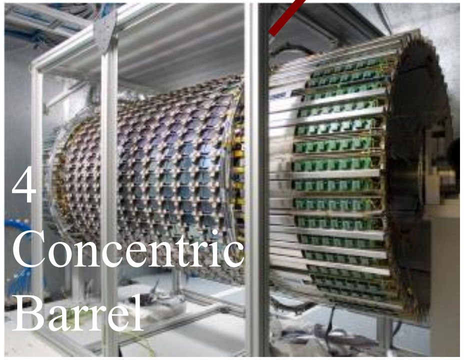
2112 Barrel and 1976 End-Cap Double-Sided Modules

$61\,m^2$ of silicon micro-strip detectors

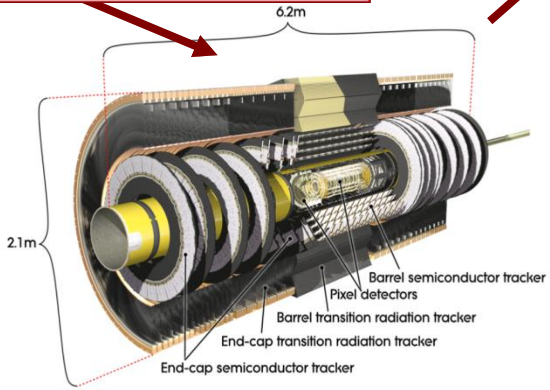
~20,000 separate sensors ordered



ATLAS



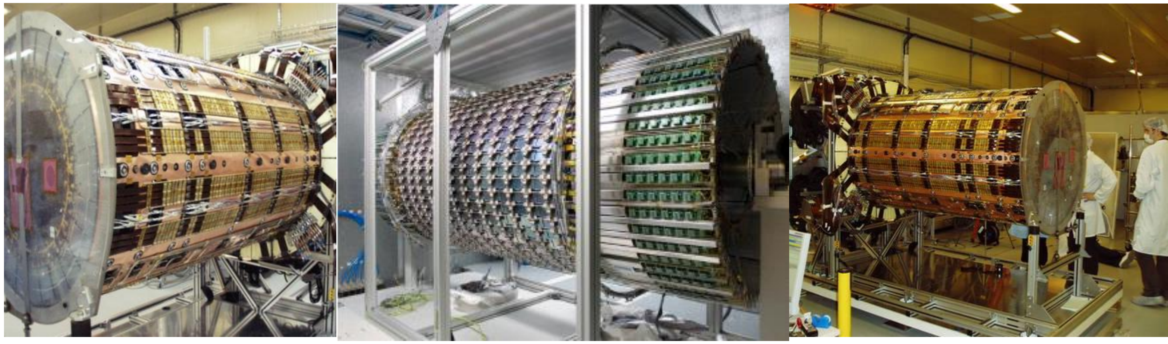
4 Concentric Barrel



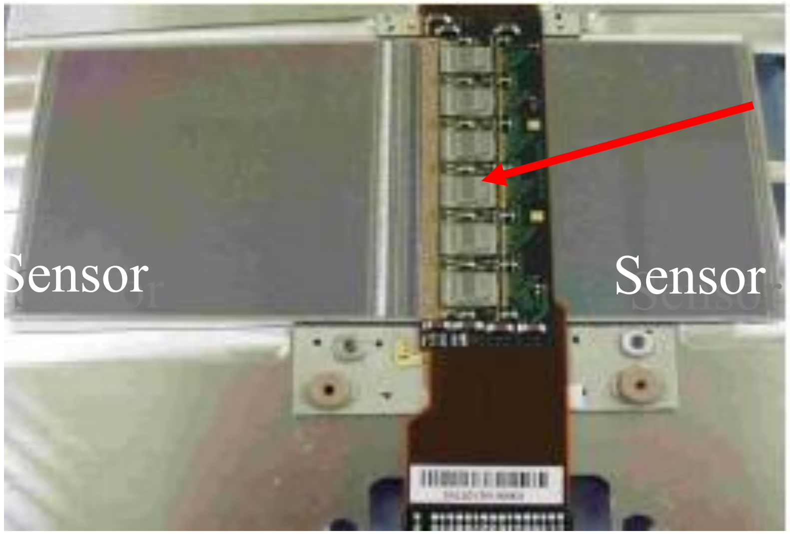
Oxford and CERN

ATLAS SCT modules

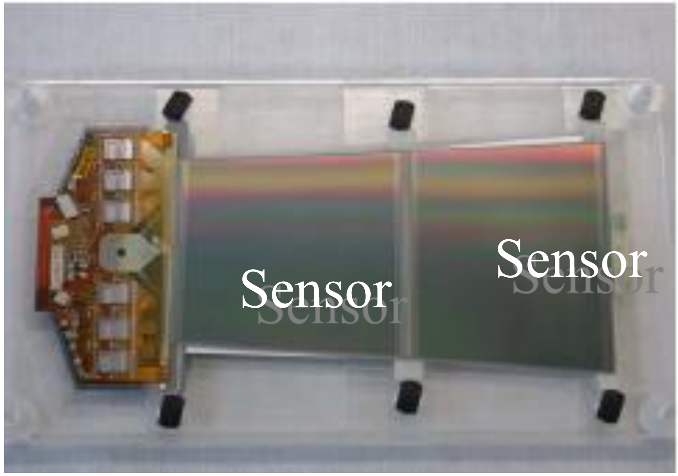
ATLAS Tracker Based on
Barrel and Disc Supports



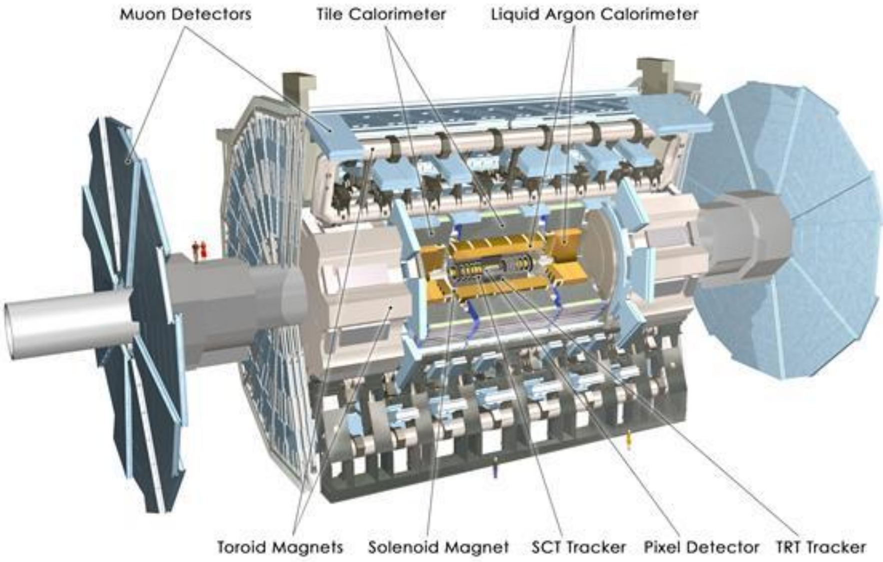
Effectively two styles of double-sided modules (2×6cm long) each sensor ~6cm wide (768 strips of 80µm pitch per side)

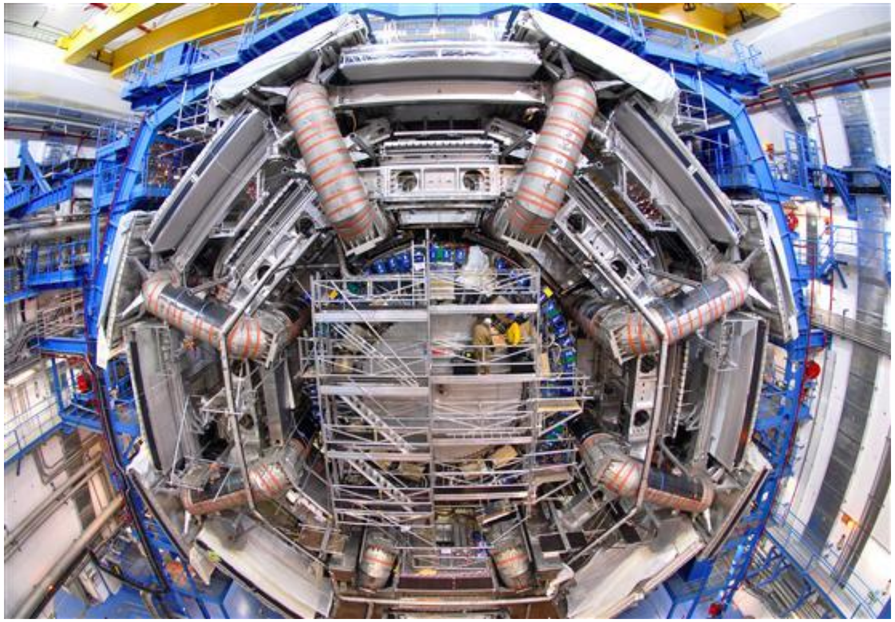


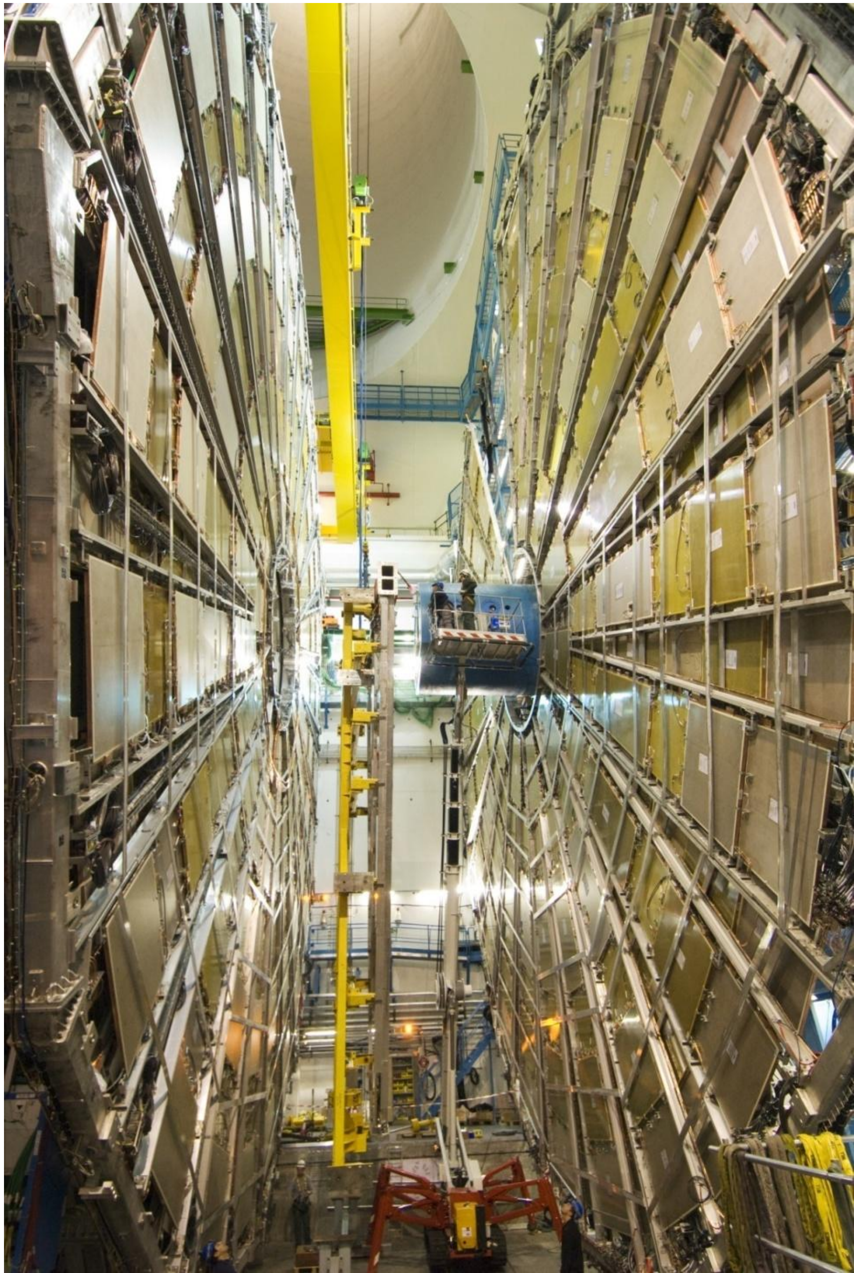
Hybrid cards carrying read- out chips and multilayer interconnect circuit



The ATLAS experiment

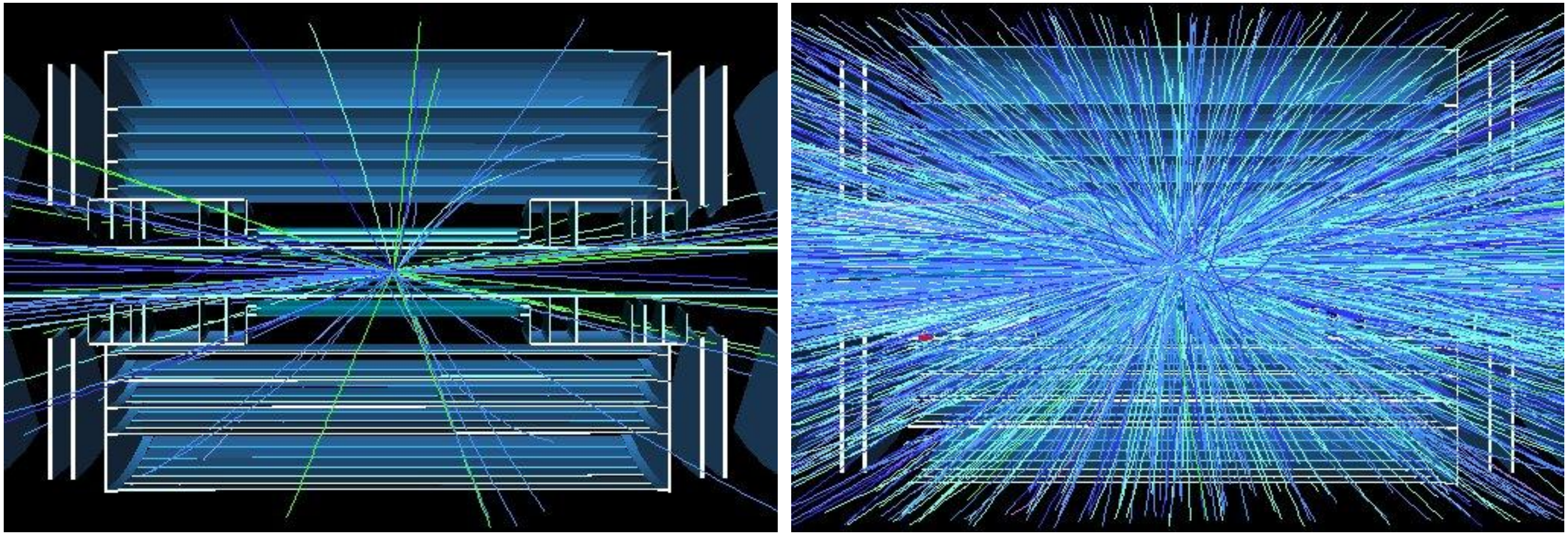




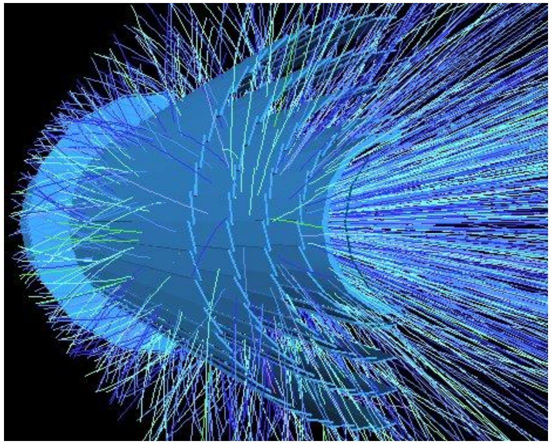


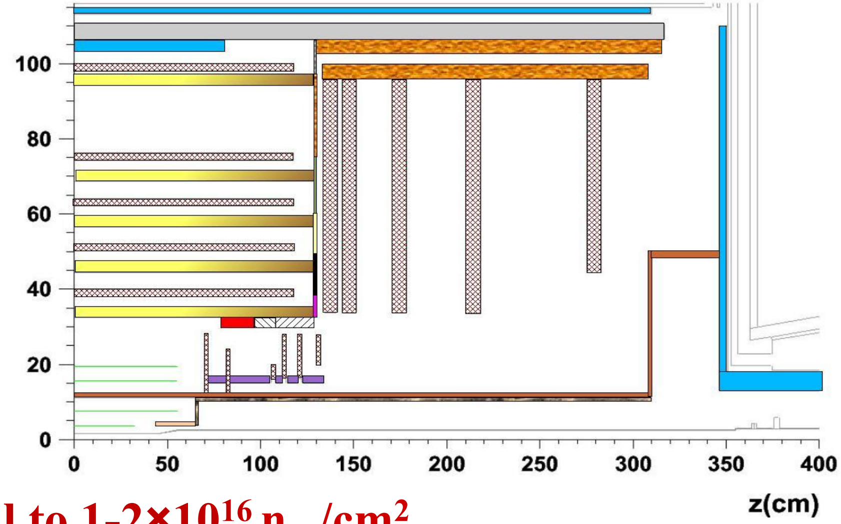
Upgrading the experiments: HL-LHC

The number of pile-up events per bunch crossing will be between 250-400! Extremely high multiplicity and radiation!



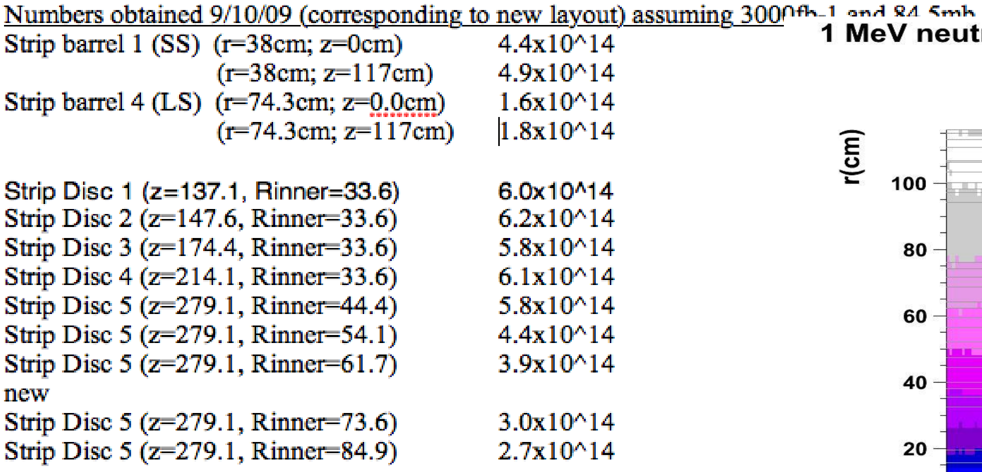
Future experiments





At inner pixel radii - target survival to 1-2×10^{16} n$_{eq}$/cm^2

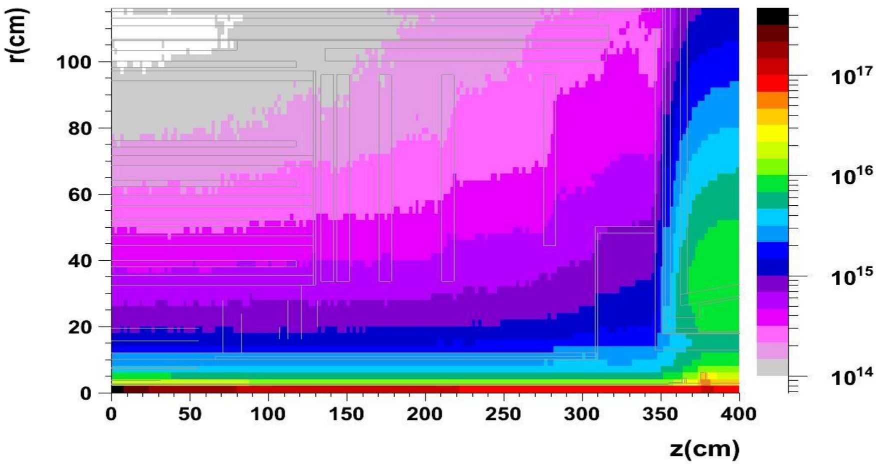
For strips ~1.3×10^{15} n$_{eq}$/cm^2



Numbers obtained 9/10/09 (corresponding to new layout) assuming 3000fb-1 and 84.5mb

Strip barrel 1 (SS)	(r=38cm; z=0cm)	4.4x10^14
	(r=38cm; z=117cm)	4.9x10^14
Strip barrel 4 (LS)	(r=74.3cm; z=0.0cm)	1.6x10^14
	(r=74.3cm; z=117cm)	1.8x10^14
Strip Disc 1	(z=137.1, Rinner=33.6)	6.0x10^14
Strip Disc 2	(z=147.6, Rinner=33.6)	6.2x10^14
Strip Disc 3	(z=174.4, Rinner=33.6)	5.8x10^14
Strip Disc 4	(z=214.1, Rinner=33.6)	6.1x10^14
Strip Disc 5	(z=279.1, Rinner=44.4)	5.8x10^14
Strip Disc 5	(z=279.1, Rinner=54.1)	4.4x10^14
Strip Disc 5	(z=279.1, Rinner=61.7)	3.9x10^14
new		
Strip Disc 5	(z=279.1, Rinner=73.6)	3.0x10^14
Strip Disc 5	(z=279.1, Rinner=84.9)	2.7x10^14

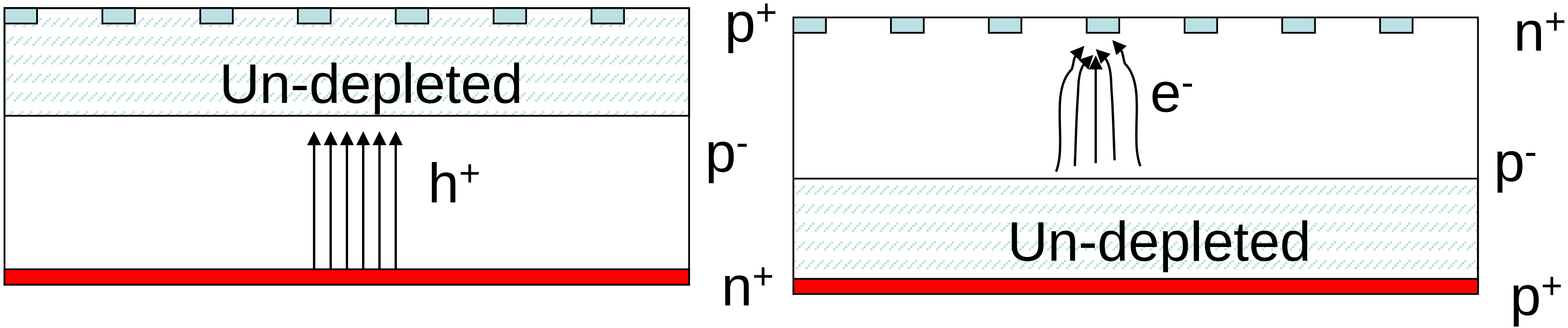
1 MeV neutron eq fluence



P-strip vs. N-strip Readout

“Standard” p-in-n geometry (after type inversion)

“New” n-in-p geometry (after type inversion)



Type inversion turns lightly doped material to “p” type

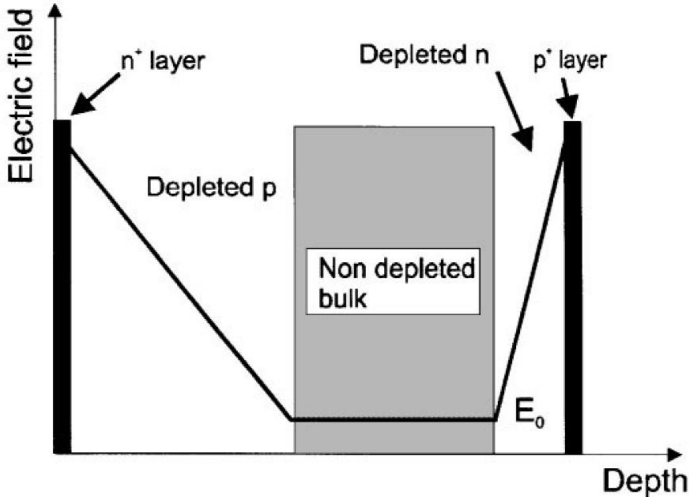
- Holes collected
- Deposited charge cannot reach electrode
  - Charge spread over many strips
  - Lower signal

- Electron collected
  - Higher mobility and ~33% smaller trapping constant
- Deposited charge can reach electrode

Radiation hardness

N-side read-out can make planar segmented Si detectors suitable for tracking in extreme (SLHC levels: 1-2x10^{16} cm^{-2}) radiation environments.

Schematic changes of Electric field after irradiation



Effect of trapping on the Charge Collection Efficiency (CCE)

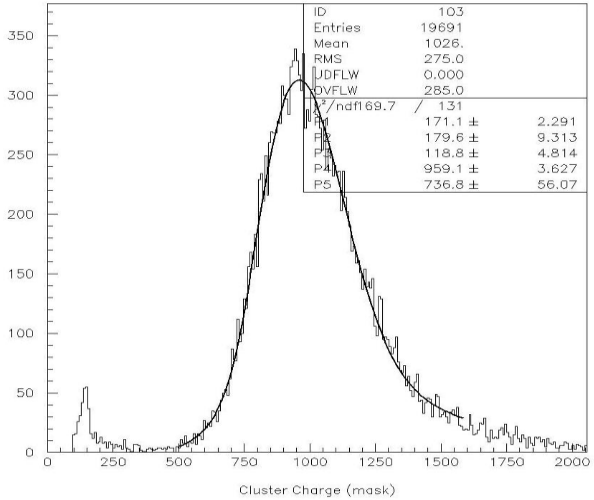
$$Q_{tc} \cong Q_0 \exp(-t_c/\tau_{tr}),\ 1/\tau_{tr} = \beta\Phi.$$

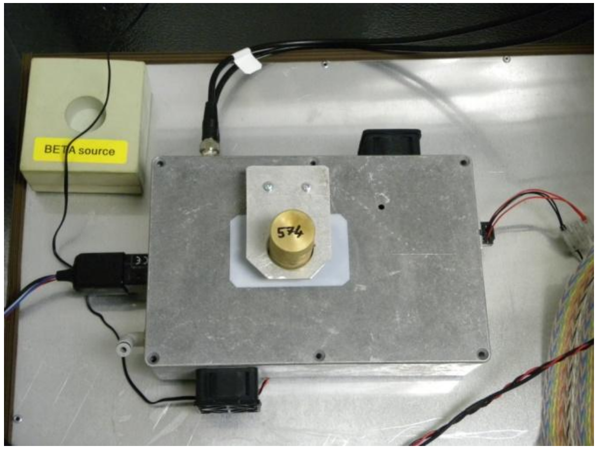
Collecting electrons provide a sensitive advantage with respect to holes due to a much shorter t_c. P-type detectors are the most natural solution for *e* collection on the segmented side.

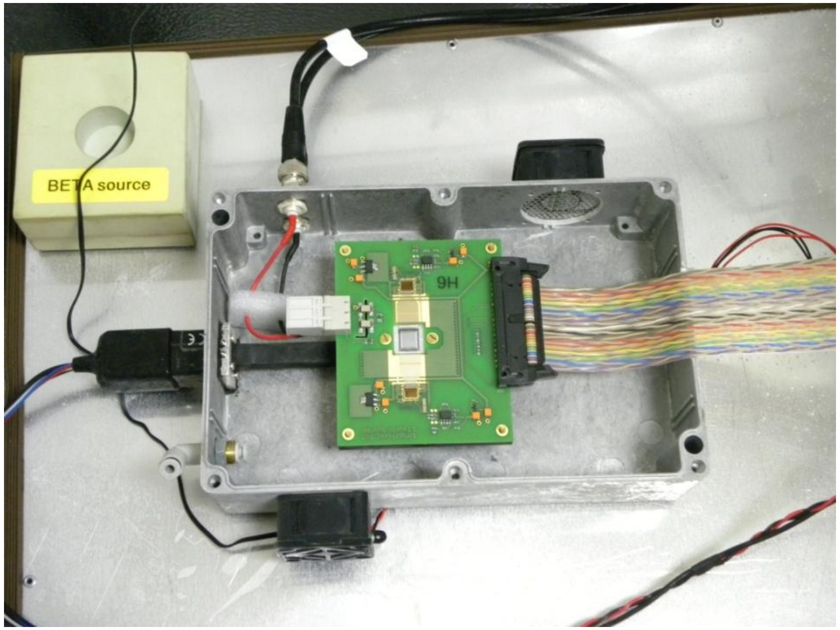
N-side read out to keep lower t_c

Radiation hardness

Mip signal from ^{90}Sr source







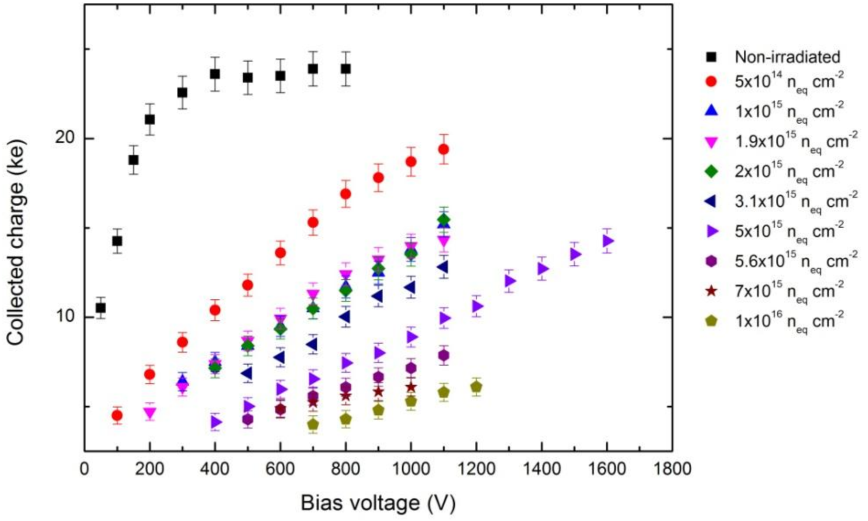
Analogue information from LHC speed analogue electronics

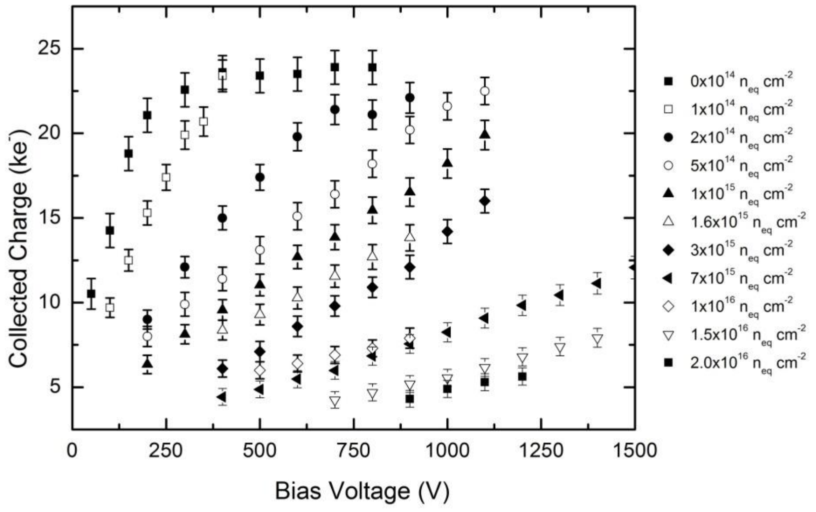
Radiation hardness

Using this method, the charge collection properties of n-in-p silicon detectors have been studied to the very highest fluences anticipated for the future HL-LHC at CERN.

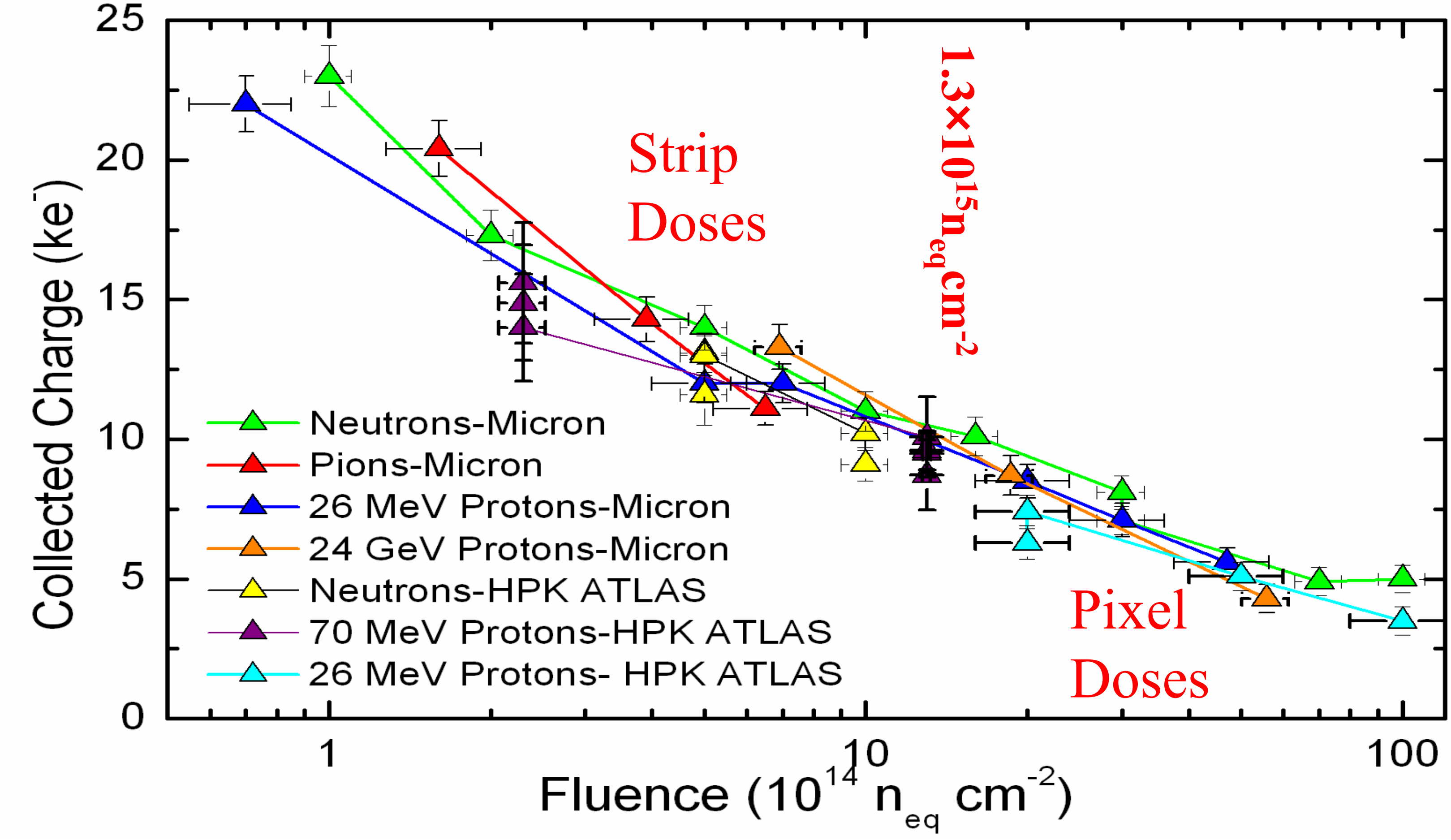
Degradation of the charge collection with 23GeV and 26MeV proton fluence of 300μm thick silicon detectors.

Degradation of the charge collection with reactor neutrons of 300μm thick silicon detectors.





Radiation hardness



Radiation hardness

Effect of trapping on the Charge Collection Distance

$Q_{tc} \cong Q_0 \exp(-t_c/\tau_{tr})$, $1/\tau_{tr} = \beta\Phi$.

$v_{sat,e} \times \tau_{tr} = \lambda_{av}$

$\beta_e = 4.2\text{E}-16\ \text{cm}^{-2}/\text{ns}$

$\beta_h = 6.1\text{E}-16\ \text{cm}^{-2}/\text{ns}$

After heavy irradiation the charge collection distance (CCD) of thin detectors should have a similar (better?) charge collection efficiency (CCE) as thicker ones.

$\lambda_{Max,n}\ (\Phi=1e14) \cong 2400\mu m$

$\lambda_{Max,n}\ (\Phi=1e16) \cong 24\mu m$

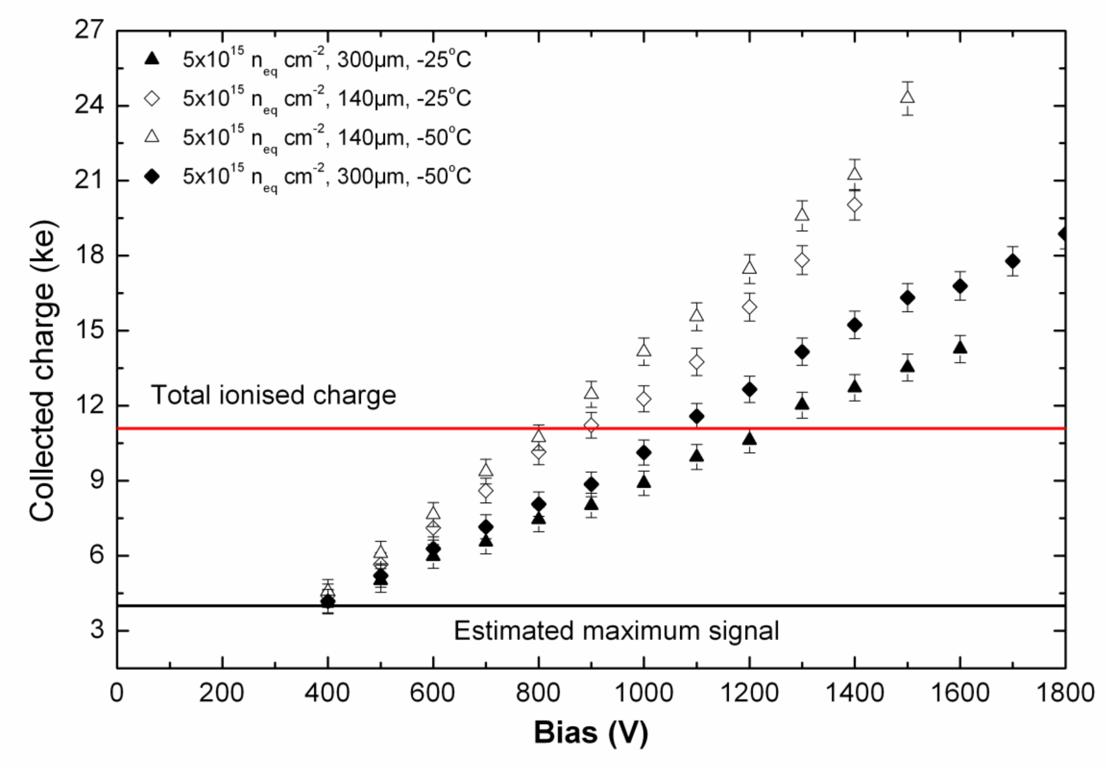
$\lambda_{Max,p}\ (\Phi=1e14) \cong 1600\mu m$

$\lambda_{Max,p}\ (\Phi=1e16) \cong 16\mu m$

The reverse current is proportional to the depleted volume in irradiated detectors. Do thin sensors offer an advantage in term of reduced reverse current compared to thicker ones (this aspect is particularly important for the inner layer detectors of SLHC, where significant contribution to power consuption is expected from the sensors themselves)?

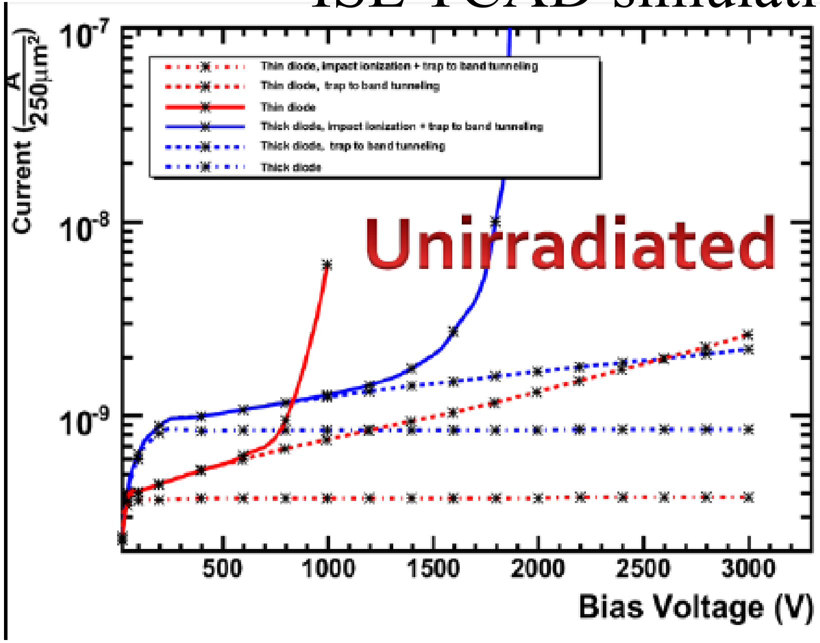
More hardness than expected

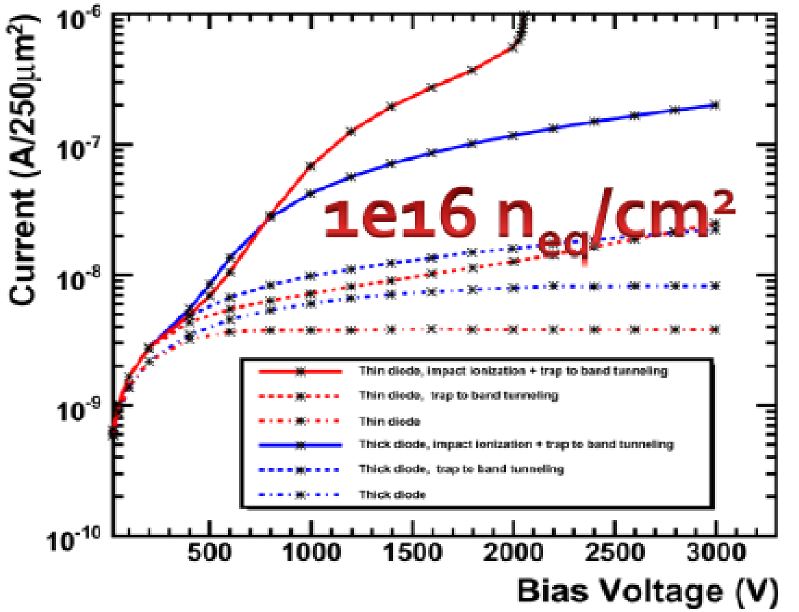
Charge multiplication by impact ionisation increases the signal after high doses!

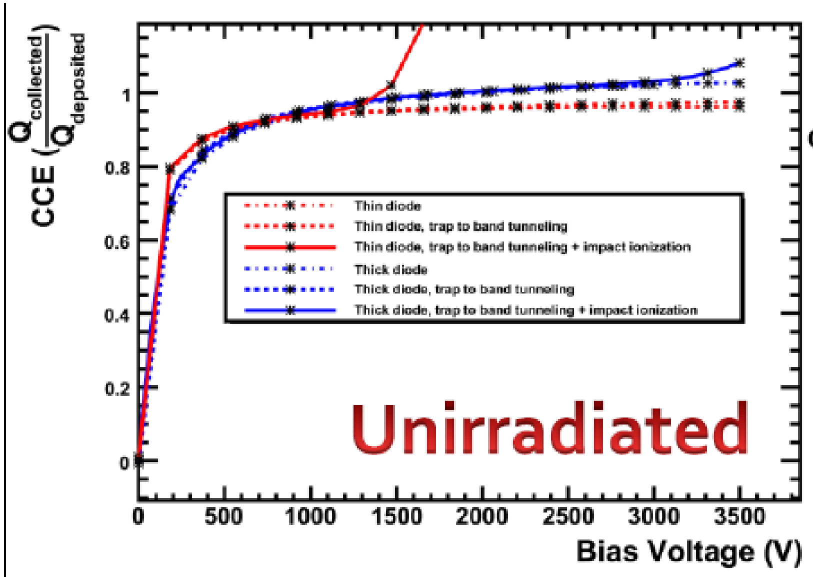


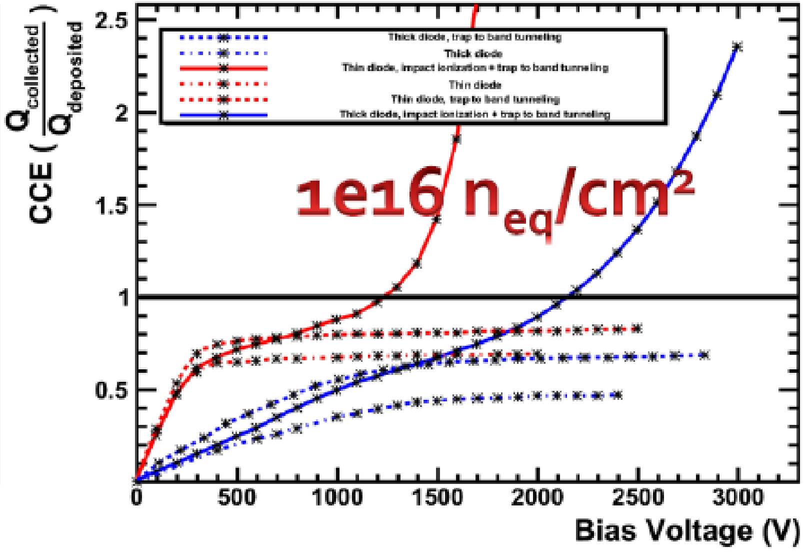
Charge multiplication

ISE TCAD simulations

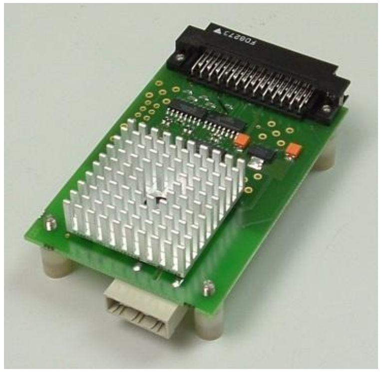


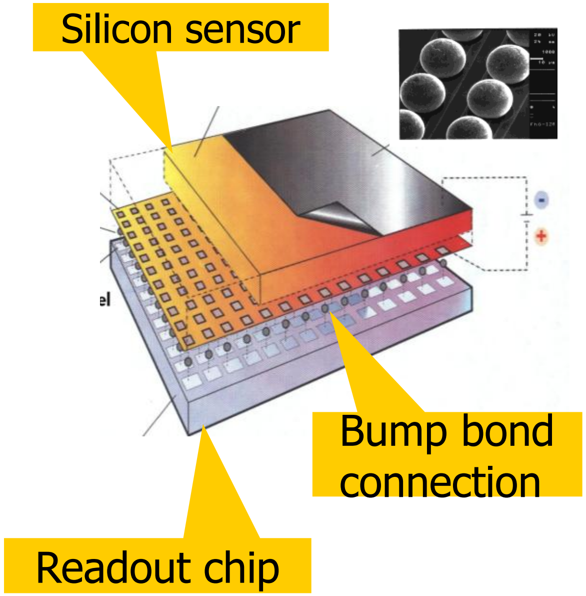


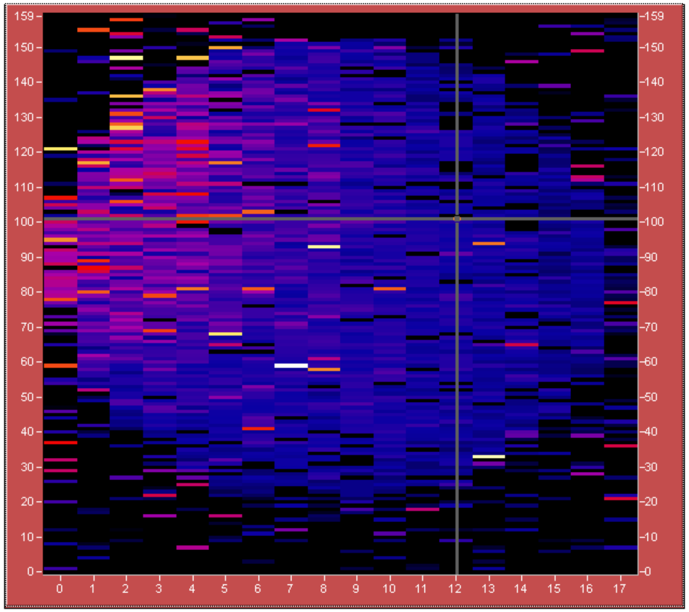




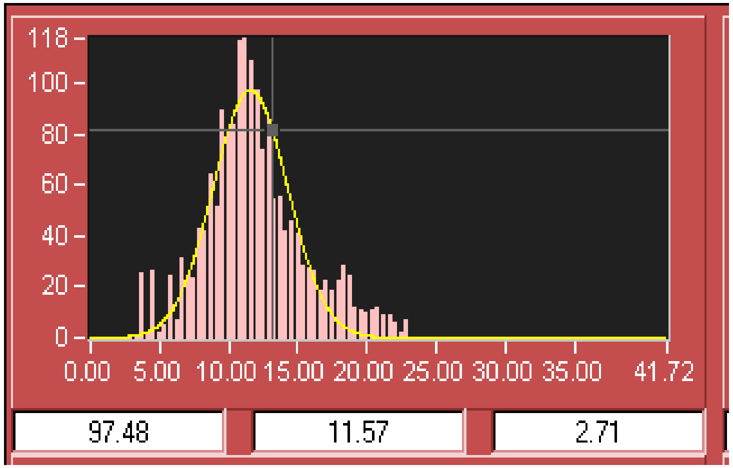
Radiation hardness and fine granularity







After irradiation to
1.5×10^{16} p/cm^2
At CERN PS
(9×10^{15} n_{eq} cm^{-2})
peak charge at
500V is ~4000e
(Threshold 3500e
-26°C, I_b 44uA)

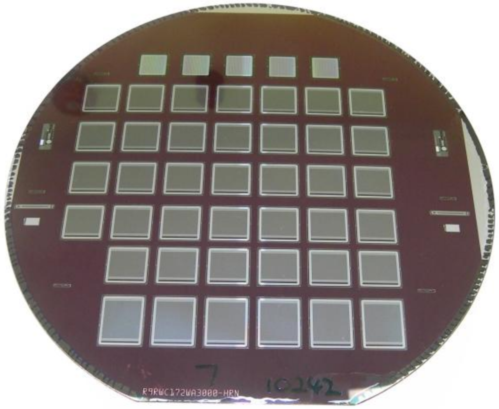


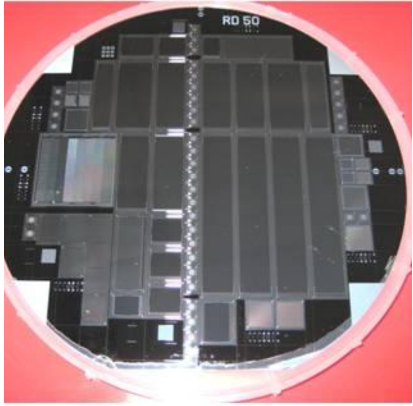
97.48

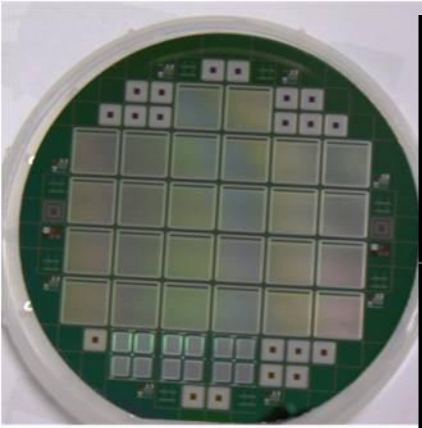
11.57

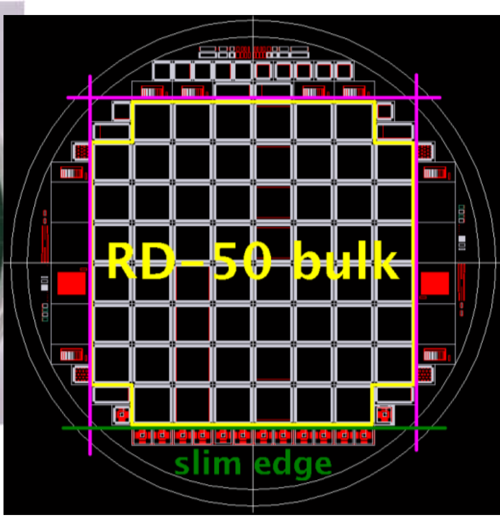
2.71

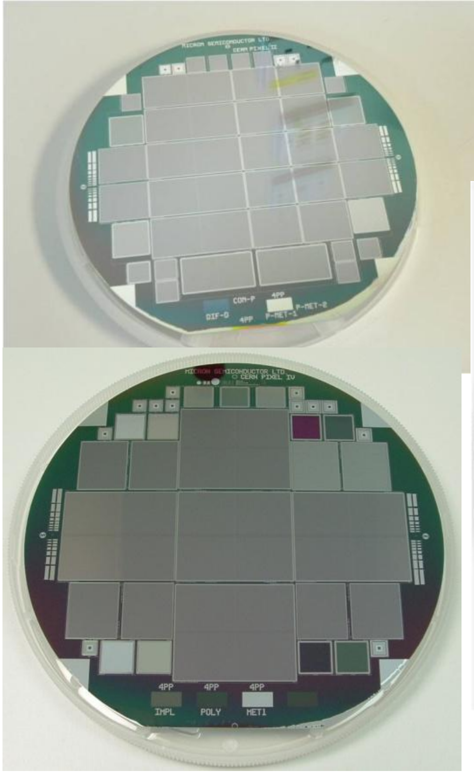
R&D for future experoments

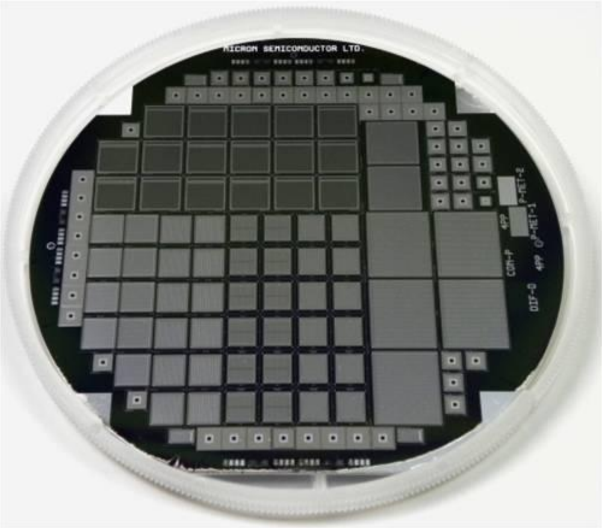












Knowledge of production procedures and technologies. Most extreme radiation tolerant devices in the world. Collaboration with different producers.