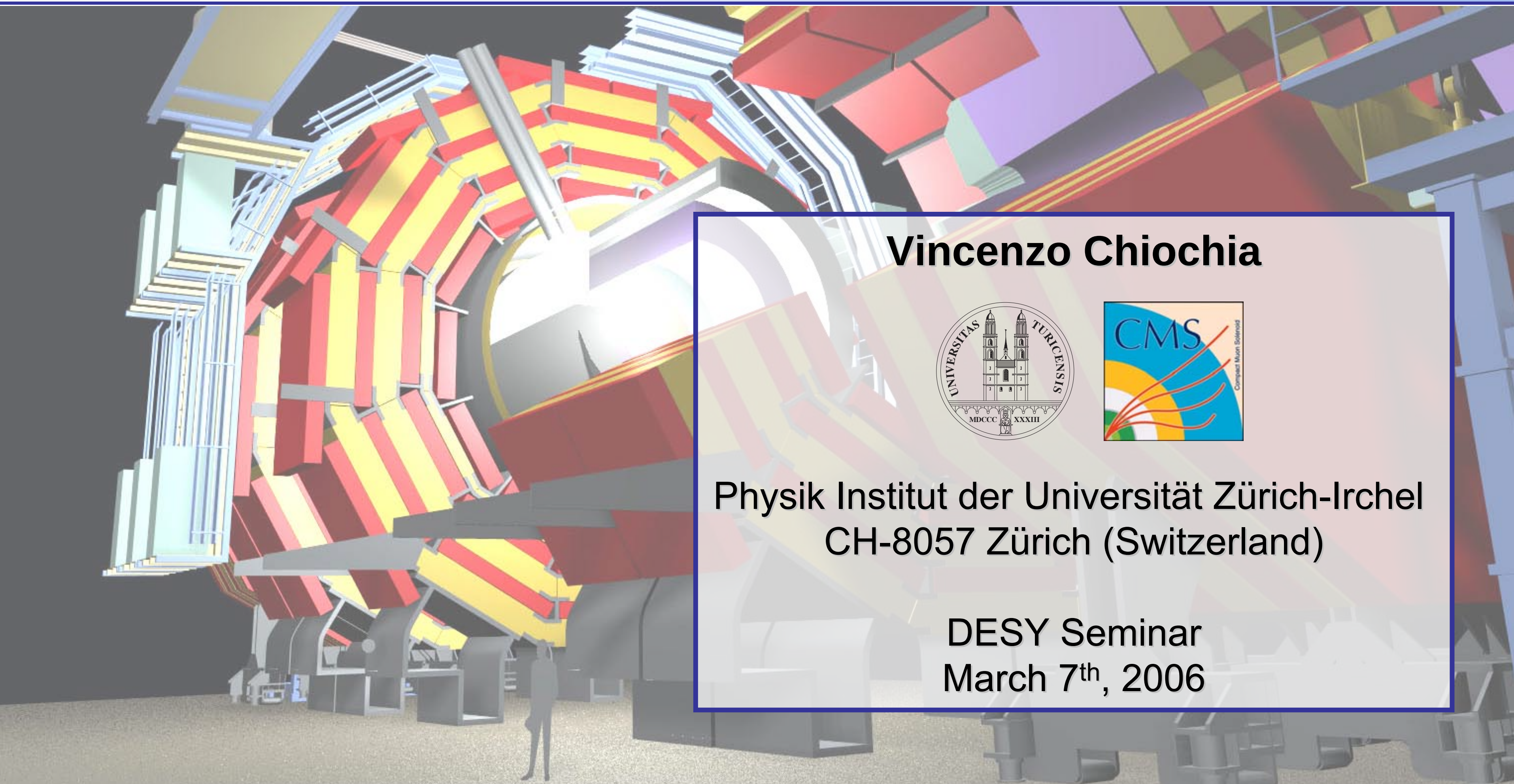
Silicon Tracking Detectors for the LHC experiments



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Outline

Part 1:

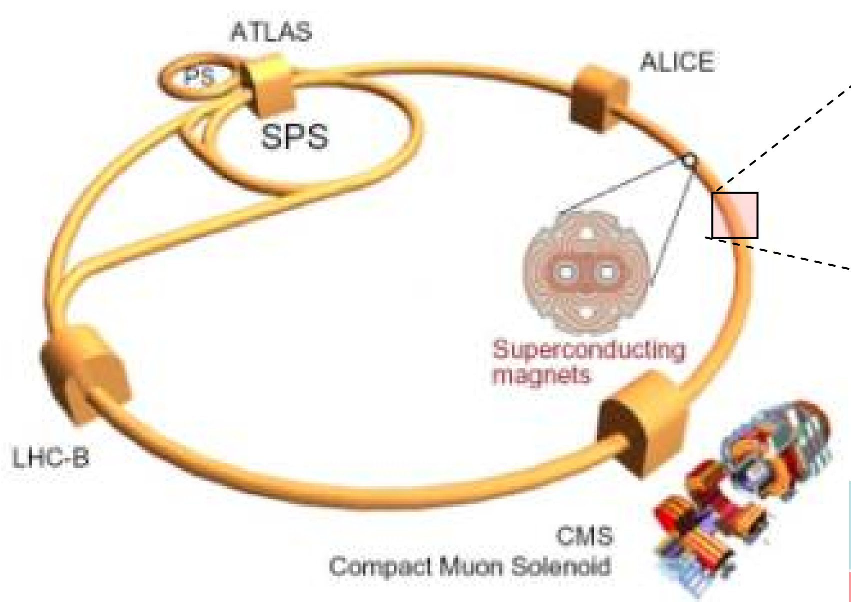
1. Tracking at the LHC experiments
2. The CMS and Atlas silicon tracker

Part 2:

1. Performance degradation with irradiation
2. Physical modelling of radiation damage
3. Model applications

Experiments at the LHC

Two super-conducting rings
in the LEP tunnel



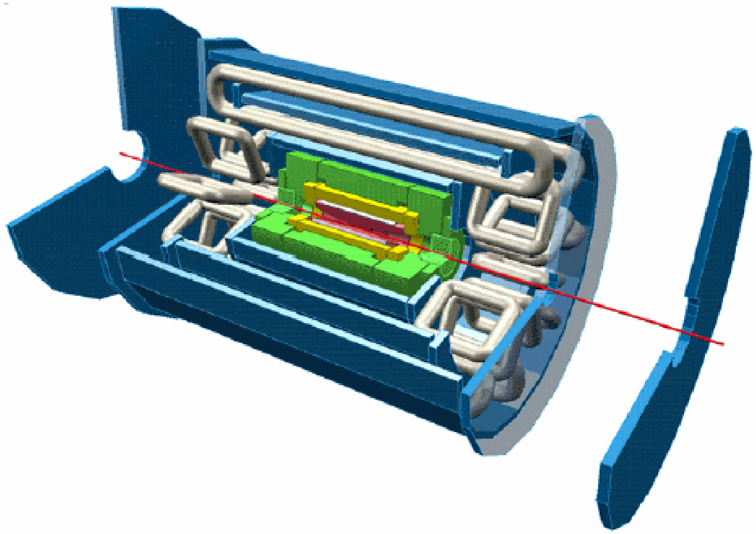
	Beam	Energy	Luminosity
LEP	e^+e^-	200 GeV	10^{32} $cm^{-2}s^{-1}$
LHC	p-p	14 TeV	10^{34} $cm^{-2}s^{-1}$
	Pb-Pb	1312 TeV	10^{27} $cm^{-2}s^{-1}$

Experiments at LHC:

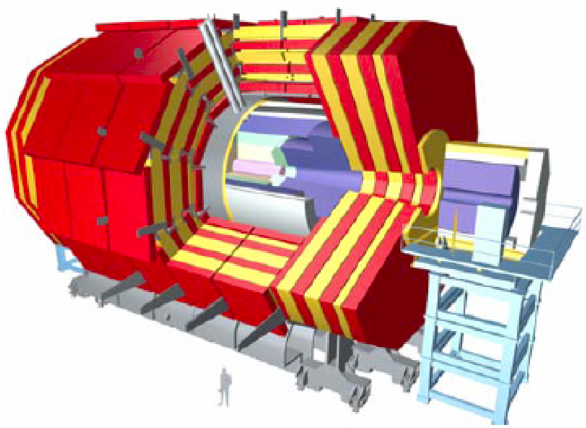
ATLAS A Toroidal LHC ApparatuS. (Study of Proton-Proton collisions)
CMS Compact Muon Solenoid. (Study of Proton-Proton collisions)
ALICE A Large Ion Collider Experiment. (Study of Ion-Ion collisions)
LHCb (Study of CP violation in B-meson decays at the LHC collider)

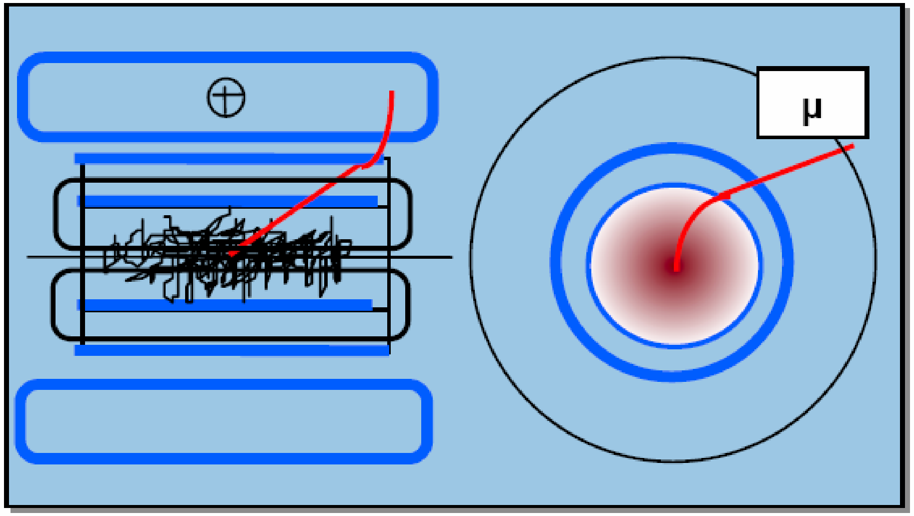
Atlas and CMS

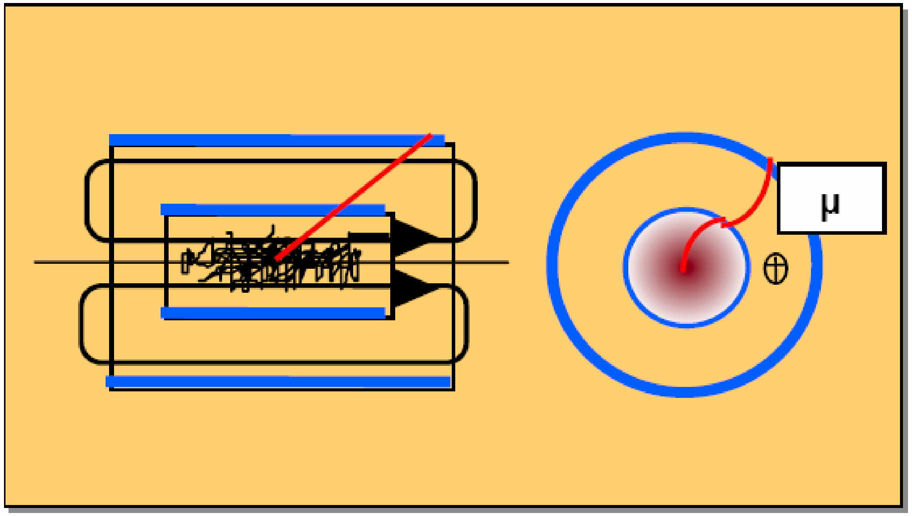
ATLAS A Toroidal LHC ApparatuS



CMS Compact Muon Solenoid







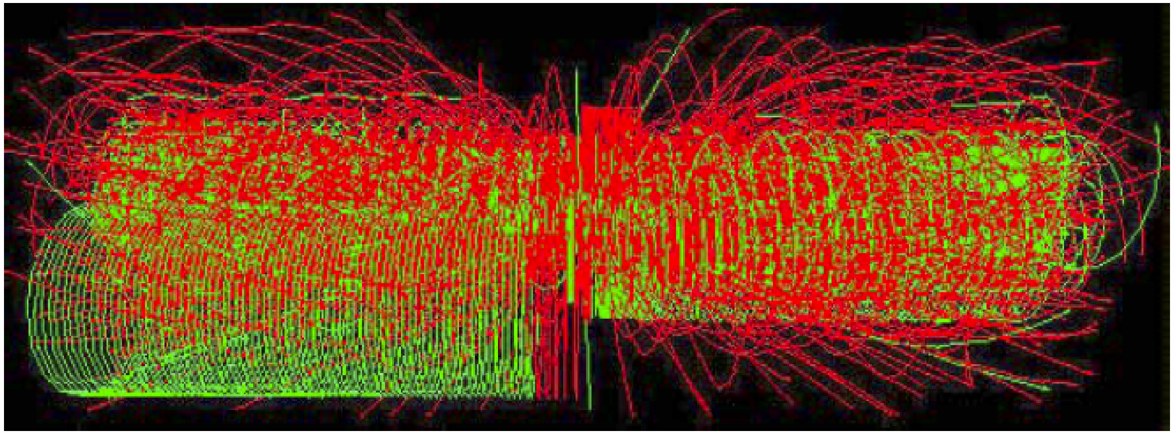
Tracking requirements at LHC

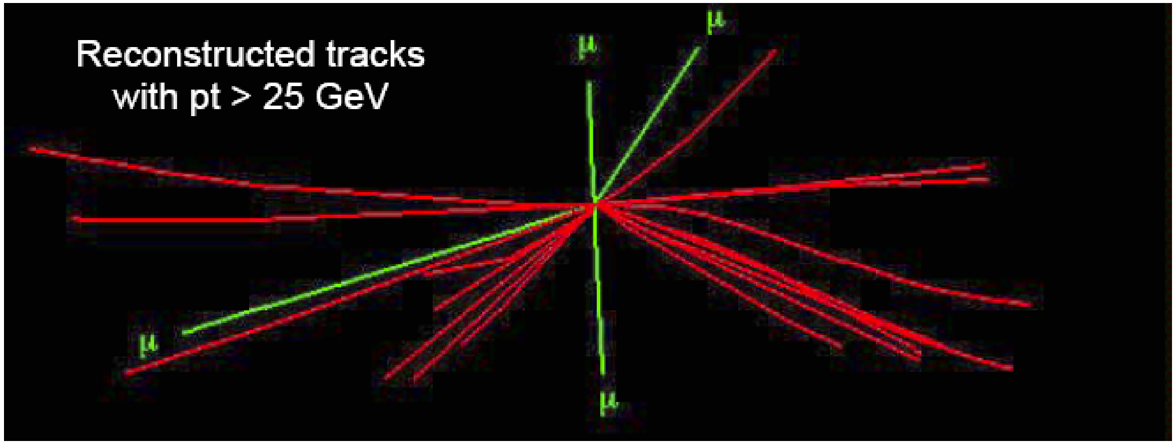
- Efficient and robust pattern recognition:
  - High speed to resolve bunch crossing
  - Fine granularity to resolve nearby tracks
- Reconstruct narrow heavy objects:
  - 1-2% P_T resolution at 100 GeV
- Tag b's and tau's through seconday vertices
- Radiation hardness of all components
  - Up to 3×10^{14} n_{eq}/cm^2/year at full luminosity in the innermost layers

Minimum bias events

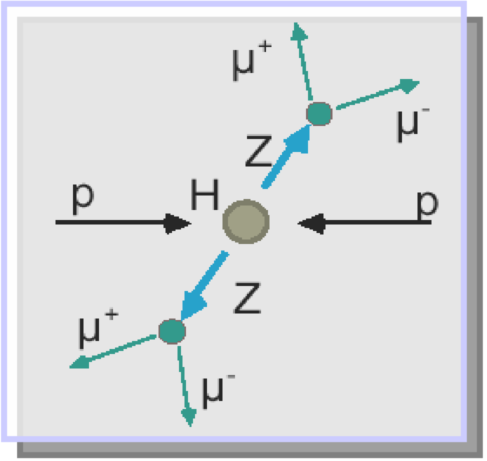
Luminosity = 10^{34} cm^{-2}s^{-1} = 10^7 mb^{-1}Hz
Interaction rate = 10^7x80 = 8x10^8 Hz
Interactions/crossing = 20

σ(pp) = 80 mb at 14 TeV
Bunch crossing = 25 ns = 2.5x10^{-8} s



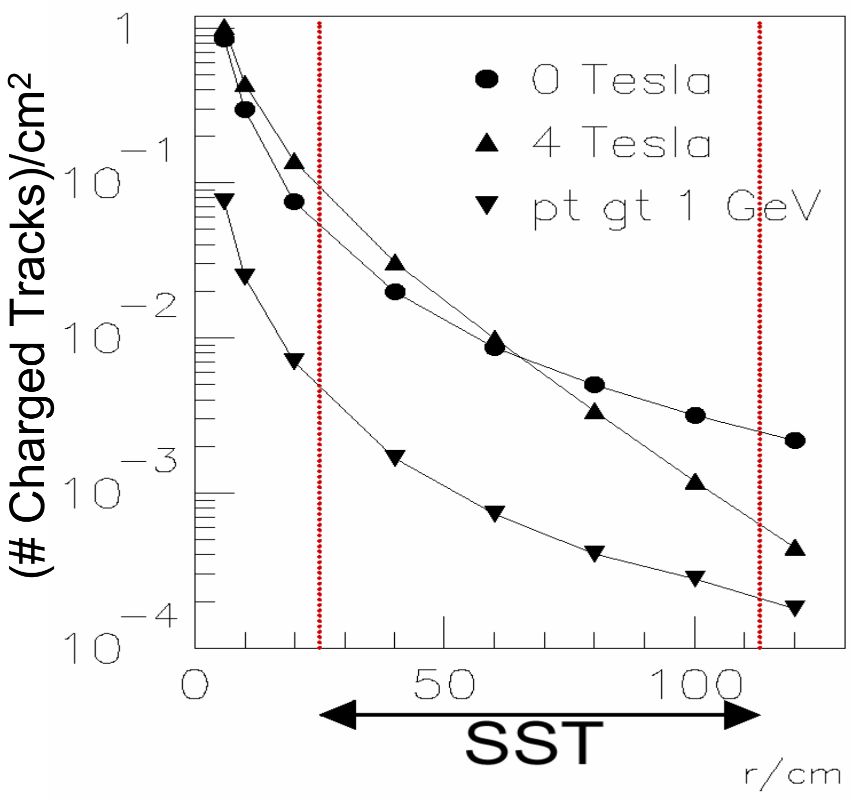


Higgs event
+
~25 minimum bias events



Detector occupancy

- Efficient and robust reconstruction with few hits requires occupancy below few %
- At small radii need cell size << 1cm^2 and fast (~25ns) shaping time.
- This condition is relaxed at large radii



Example: CMS Tracker

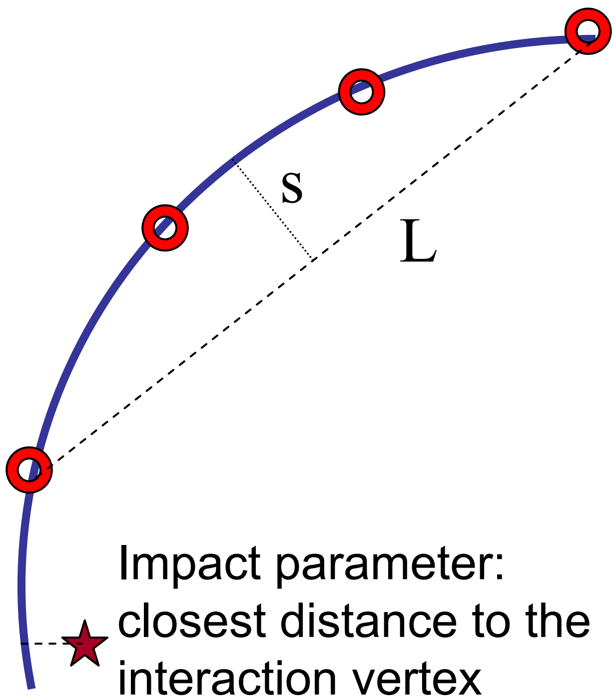
Innermost layers:
Pixels - Size=100x150 μm^2

Strip length ranges from
10cm in the inner layers to
20cm in the outer layers

Pitch ranges from
80μm in the inner layers to
~200μm in the outer layers

Detector channels = $\mathcal{O}(10^7)$

Momentum measurement



Impact parameter:
closest distance to the
interaction vertex

P ~ radius of curvature of track
~ 1 / Sagitta

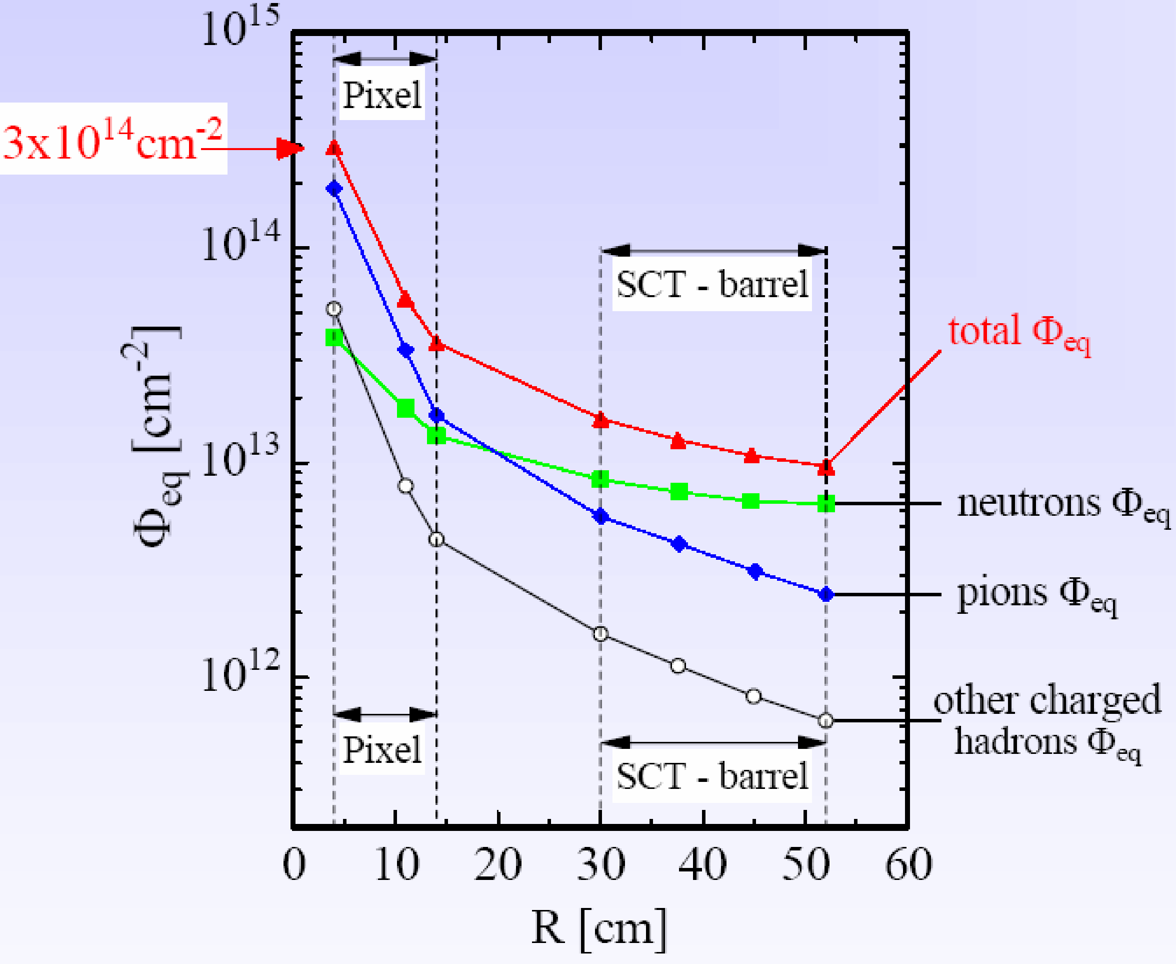
Goal:
$\Delta P_t / P_t \sim 0.1 \cdot P_t$ (P_t in TeV)
allows to reconstruct $Z \rightarrow \mu^+\mu^-$ with
$\Delta m_Z < 2$ GeV up to $P_t \sim 500$GeV

Example:
Twelve measurement layers
Spatial resolution=(Pitch/$\sqrt{12}$)
Radius = 110 cm

$$\frac{\Delta p}{p} \approx 0.12 \left(\frac{pitch}{100\mu m} \right)^1 \left(\frac{1.1m}{L} \right)^2 \left(\frac{4T}{B} \right)^1 \left(\frac{p}{1Tev} \right)$$

Result:
Pitch in the rϕ direction: around 100 μm
Spatial resolution ~ 20-40 μm

Radiation hardness



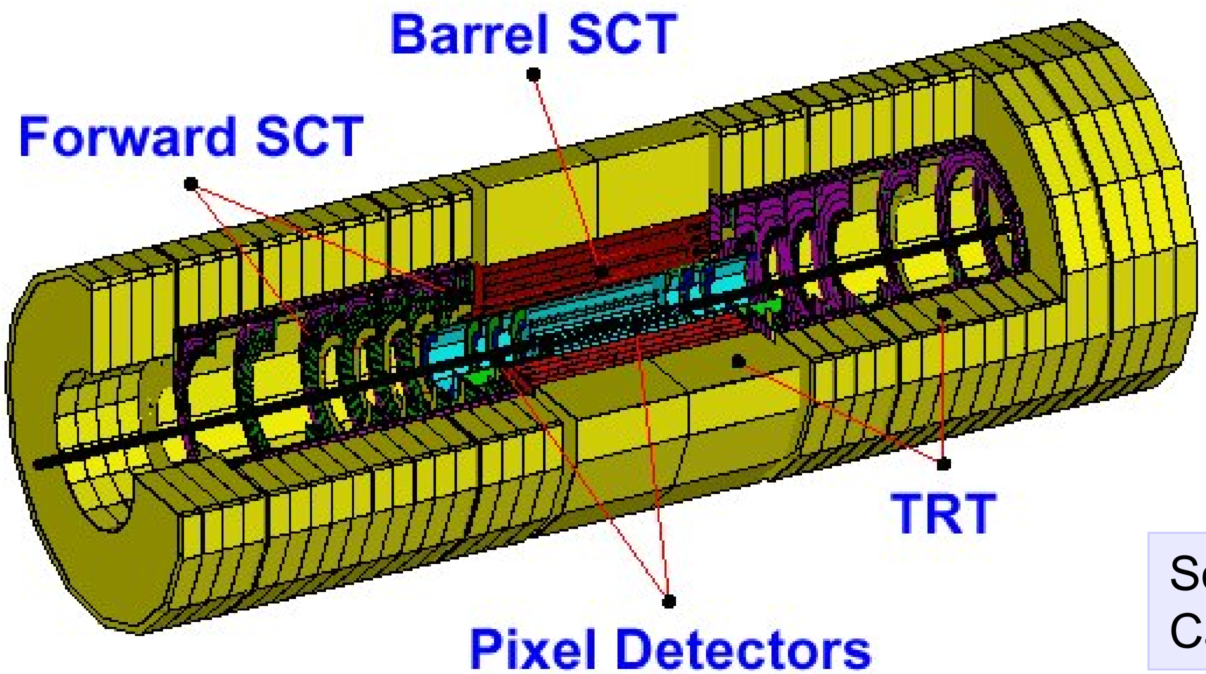
Fluence per year at full luminosity

$\sigma_{pp}^{inelastic} = 80$ mb
$L = 10^{34}$ cm^{-2}s^{-1}

- **4 cm layer $\Phi = 3 \times 10^{14}$ n/cm^2/yr**
- Fluence decreases quadratically with the radius
- Pixel detectors = 4-15 cm mostly pion irradiation
- Strip detectors = 20-110 cm mostly neutron irradiation

What is the sensors response after a few years of operation?

Atlas tracker



Solenoidal field = 2 T
Calorimeters outside solenoid

- The Inner Detector (ID) is organized into:
  - Pixels (~8×10^7 channels)
  - Silicon Tracker (SCT) (~6×10^6 channels)
  - Transition Radiation Tracker (TRT) (~4×10^5 channels)

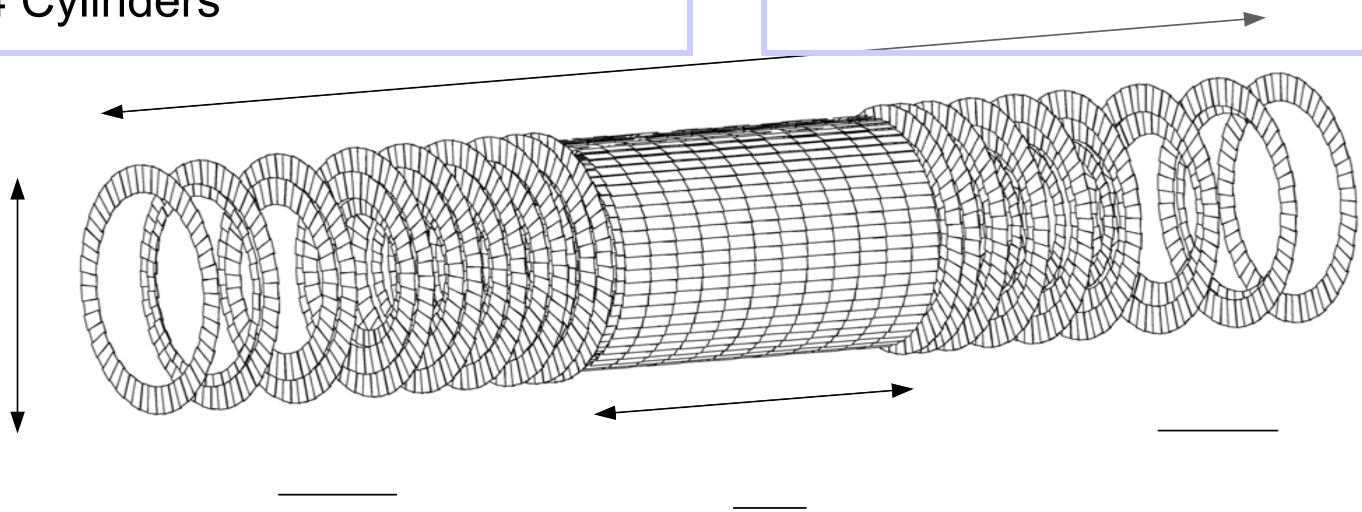
Atlas Semi-Conductor Tracker

Barrel

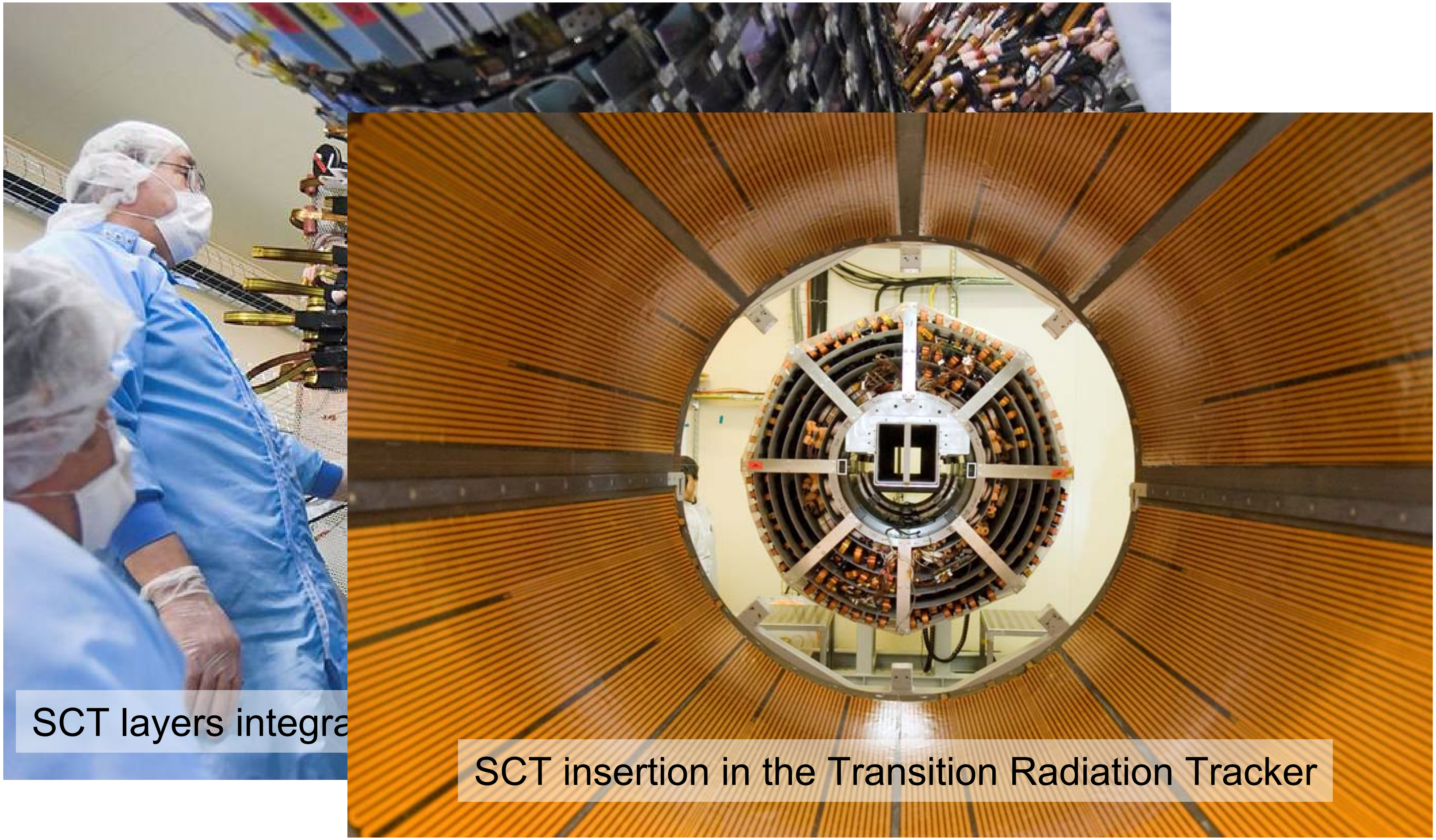
- 34.4 m^2 of silicon
- ~3.2 x 10^6 channels
- 2112 barrel modules (1 type)
- Space point resolution:
  - rφ ~ 16 mm
  - Z ~580 mm
- Coverage: |η| < 1.1 to 1.4
- 4 Cylinders

Forward

- ~26.7 m^2 of silicon
- ~3.0 x 10^6 channels
- 1976 modules (4 types)
- Space point resolution:
  - rφ ~ 16mm
  - R ~580 mm
- Coverage: 1.1 to 1.4 <|η| < 2.5
- 9 disks

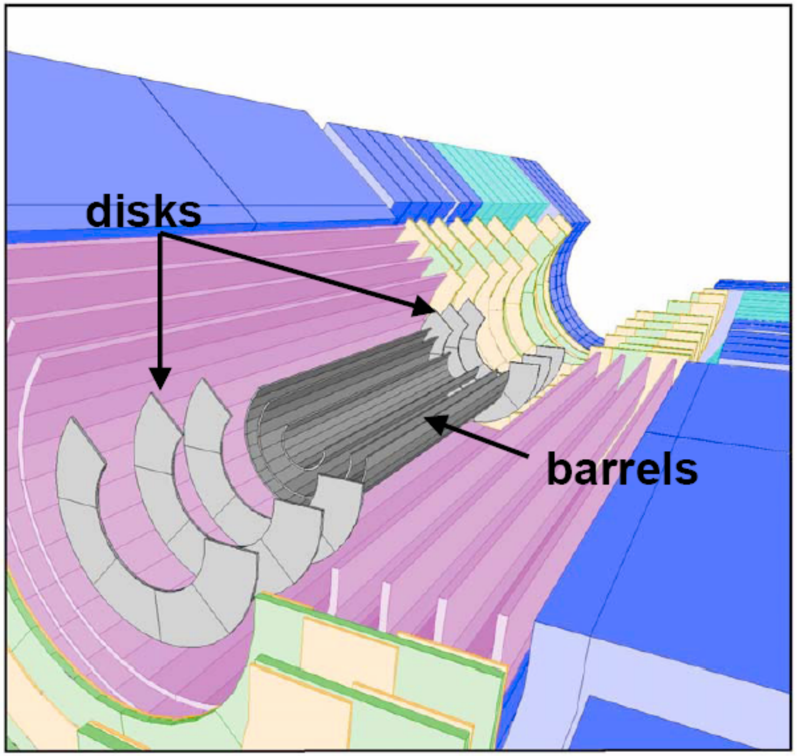


Atlas SCT integration

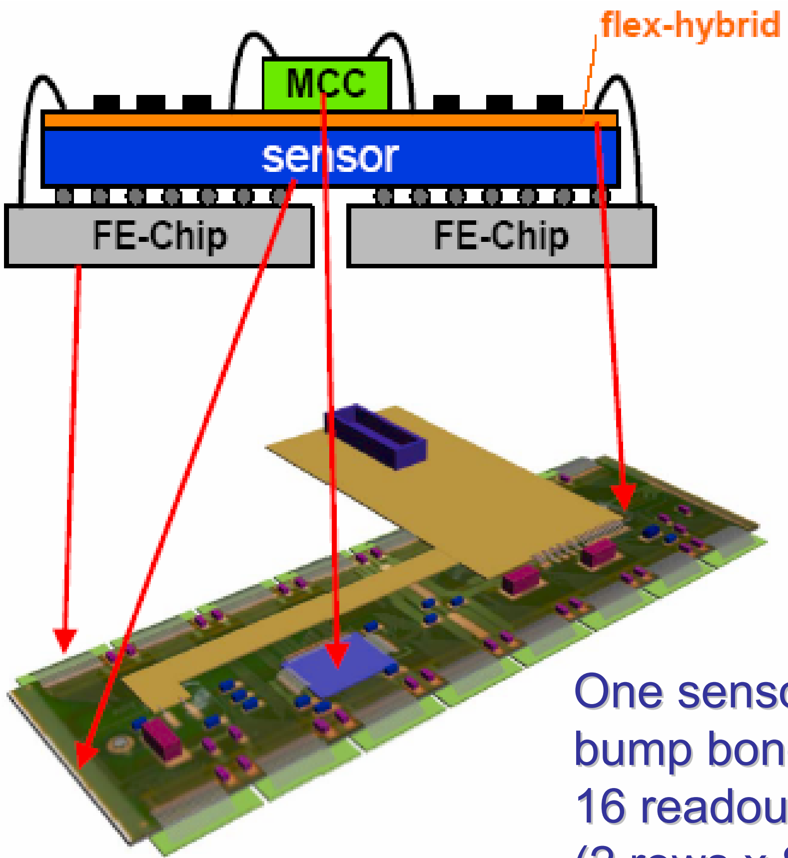


Silicon and TRT tracker integrated on February 17th, 2006

Atlas Pixel Detector



Technology: Hybrid pixels
1744 Readout modules
8×10^7 pixel cells



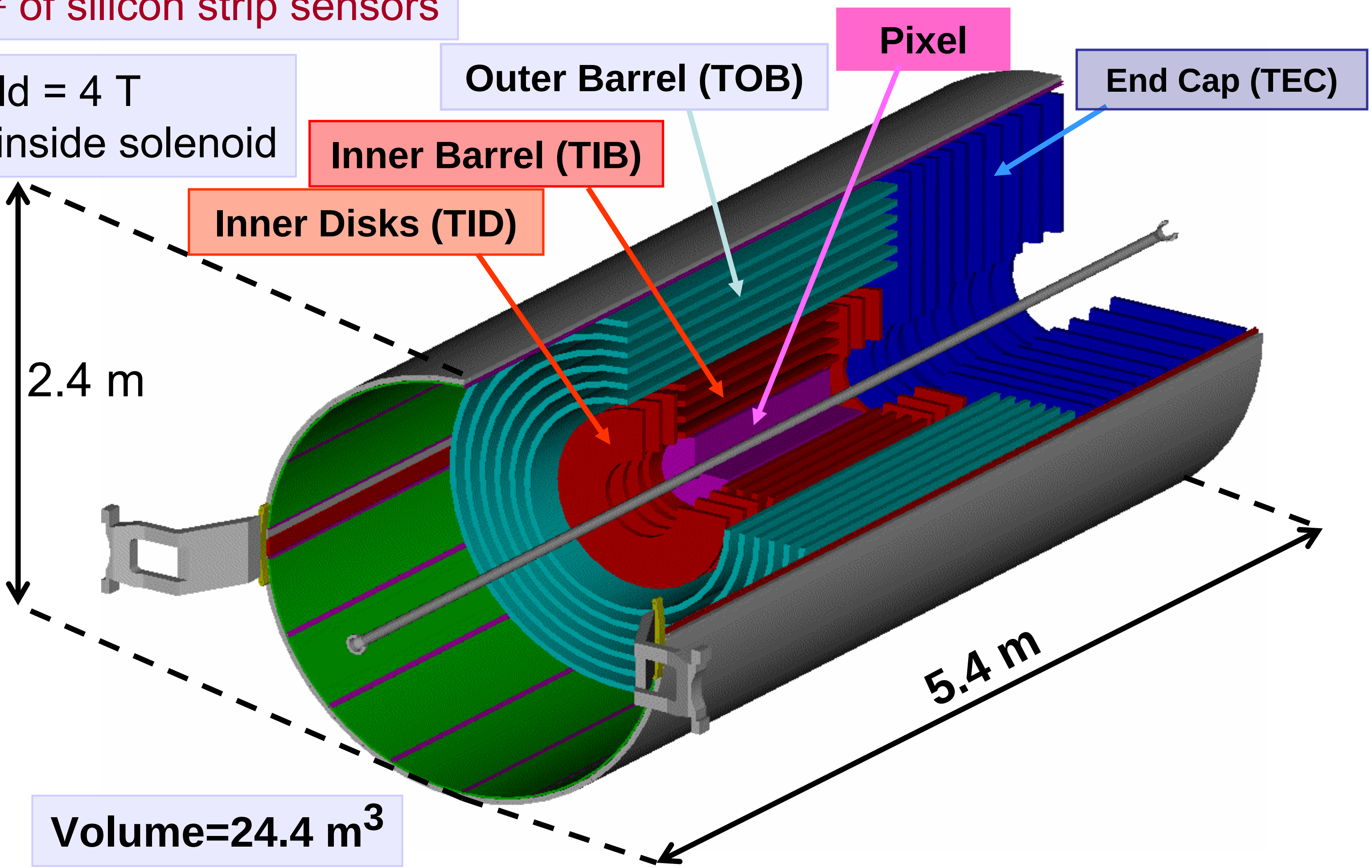
Structure:
3 Barrel layers and 3 disks on each side
Innermost layer: r=5 cm
Length ~ 1.3 m (3 hits for $|\eta|<2.5$)

One sensor bump bonded to 16 readout chips (2 rows x 8 chips)

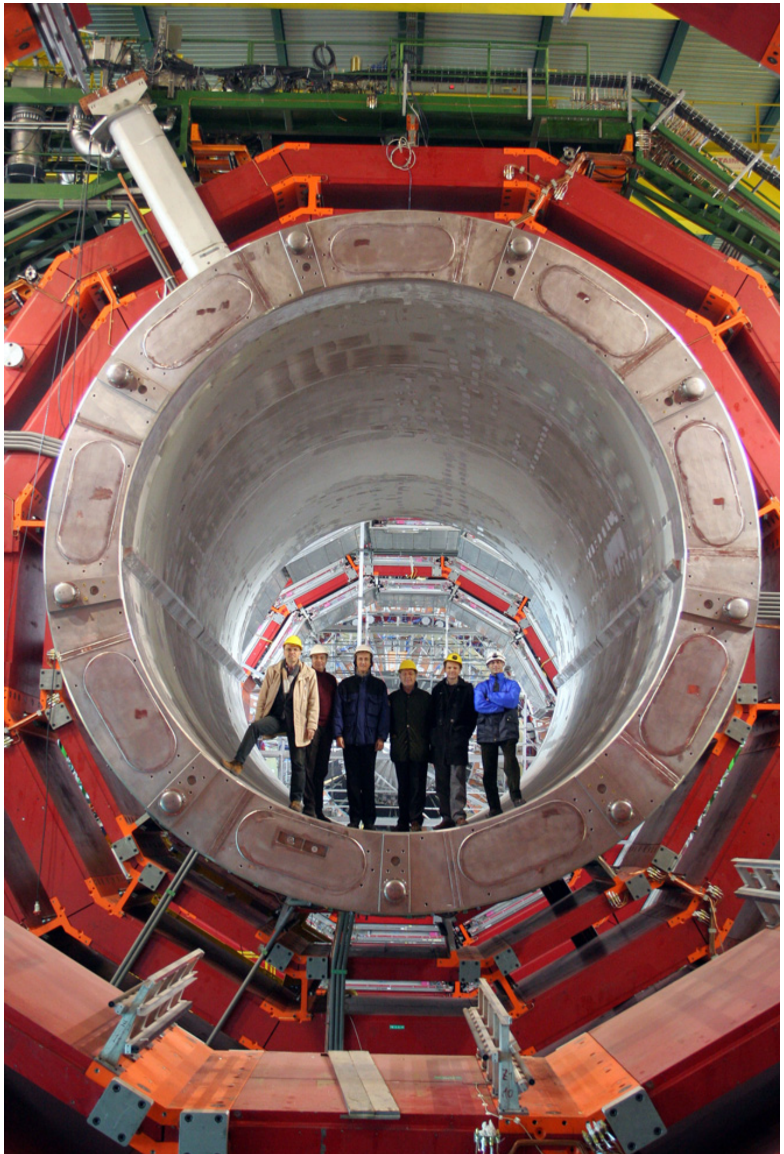
CMS Silicon Tracker

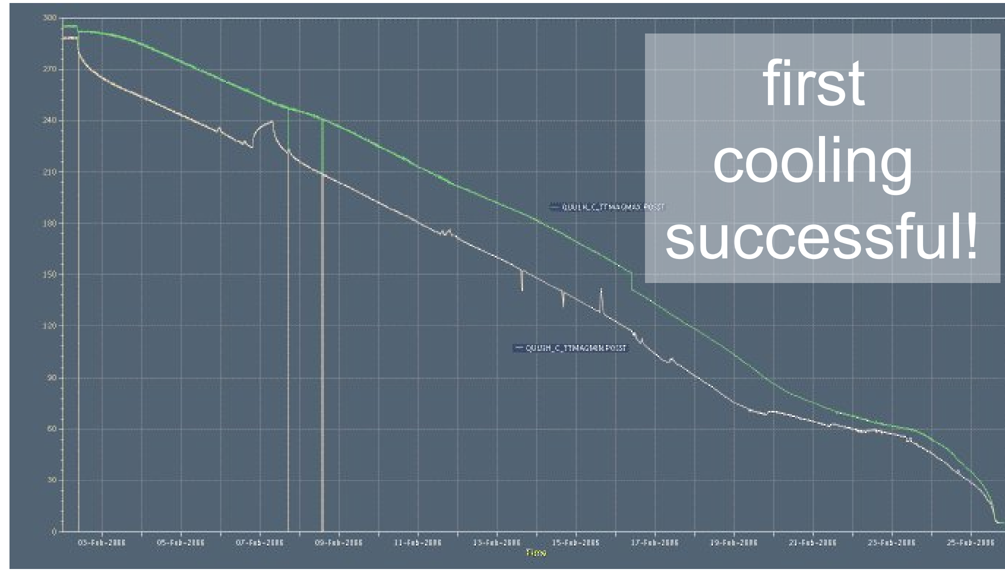
CDF & DØ ~ few m²
ATLAS ~ several *10m²
CMS ~ 210m² of silicon strip sensors

Solenoidal field = 4 T
Calorimeters inside solenoid



CMS Solenoid





23 days, 9 hours cooling down

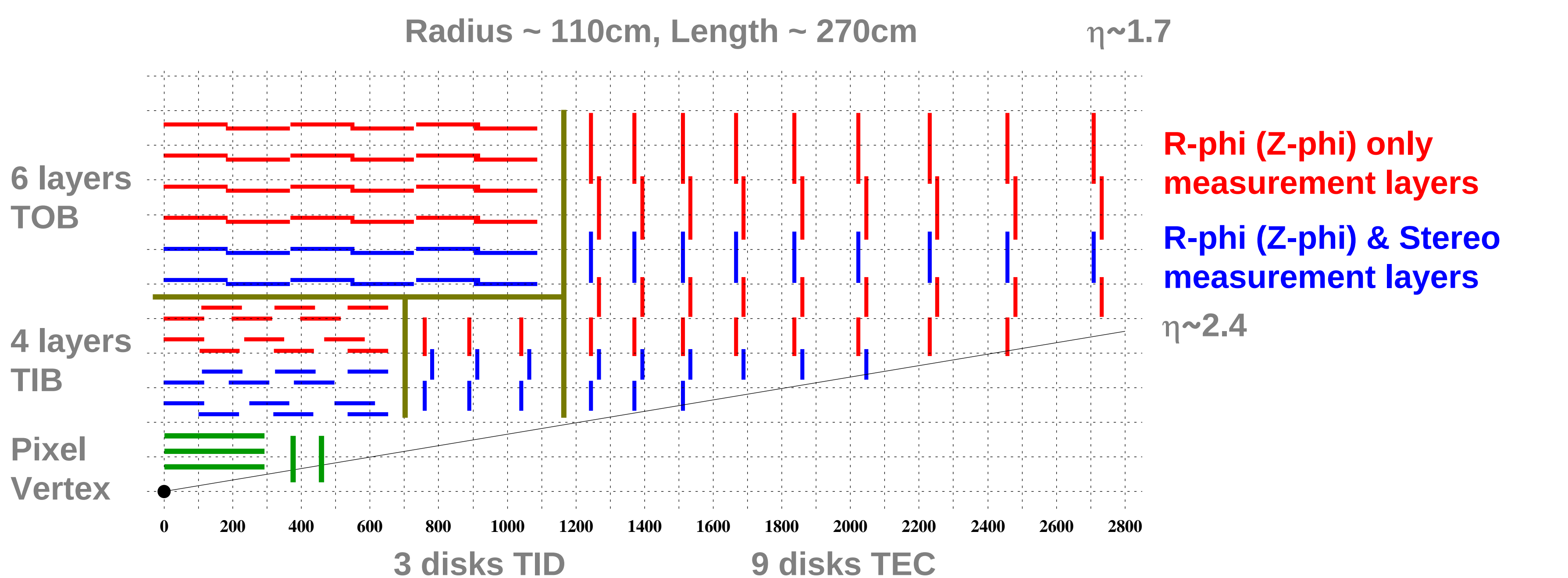
Conductor:
Superconductor cable (14.5 tonnes)
embedded in very pure aluminum (74 tonnes).
Structure:
Aluminum alloy (126 tonnes)
Insulation (9 tonnes),
Total mass of = 223.5 tonnes

B field = 4 T

CMS Silicon Tracker

Quarter of the CMS Tracker along the beam axis

Radius ~ 110cm, Length ~ 270cm



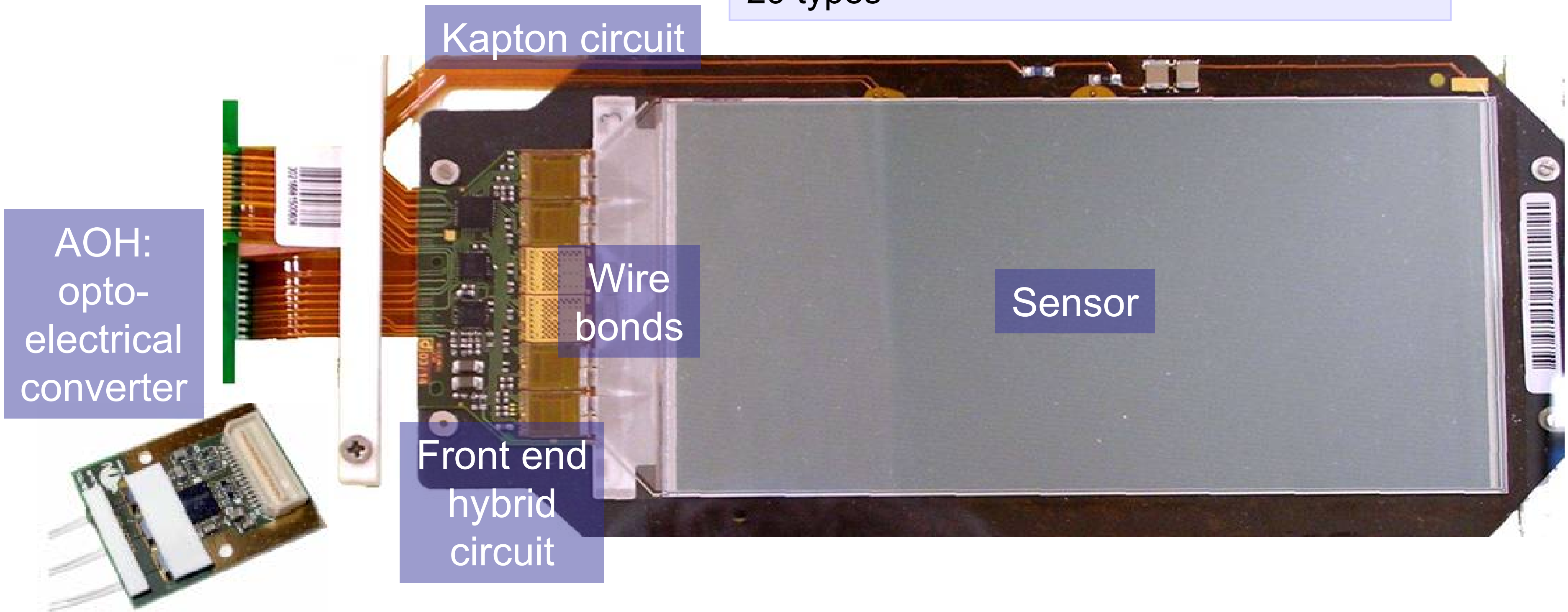
- Rely on "few" measurement layers, each able to provide robust (clean) and precise coordinate determination:
  - 2 to 3 silicon pixel hits
  - 10 to 14 silicon strip hits

CMS SST: The components

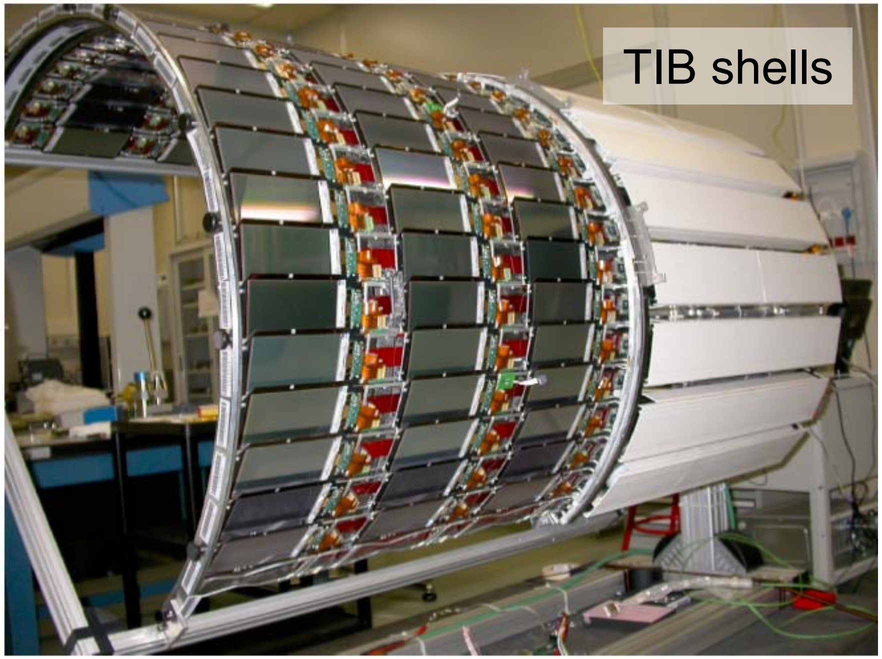
Sensors:
6,136 Thin + 18,192 Thick sensors
512 or 768 strips
Rectangular or trapezoidal sensors
9,648,128 strips = channels

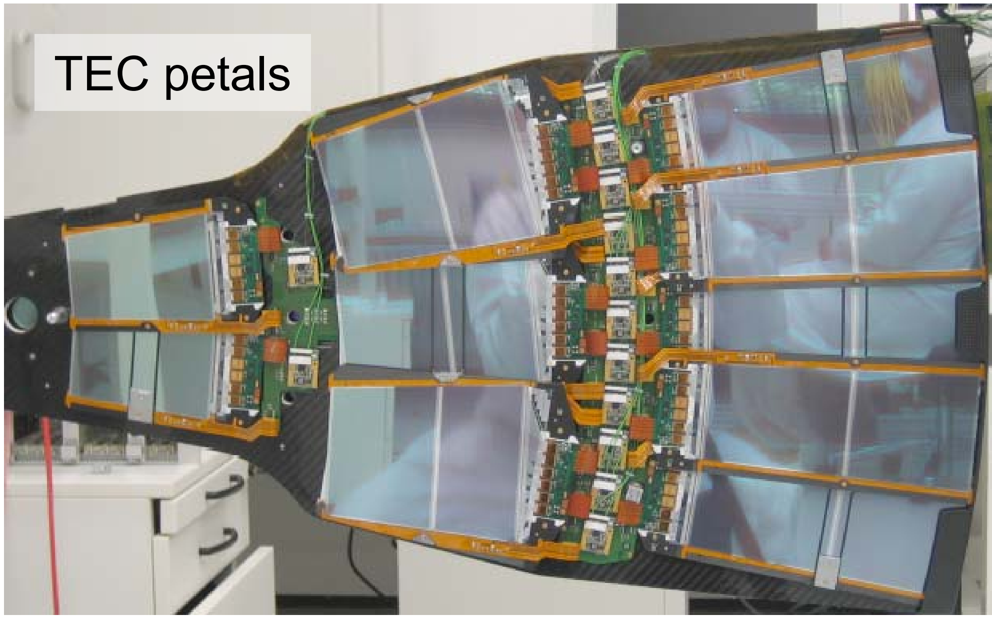
Front-end chips:
75,376 APV Chips (0,25 μm CMOS)
Sampling: Peak and deconvolution mode
128 ch, 4.8 μs pipeline depth
25 million wire bonds

Modules:
29 types

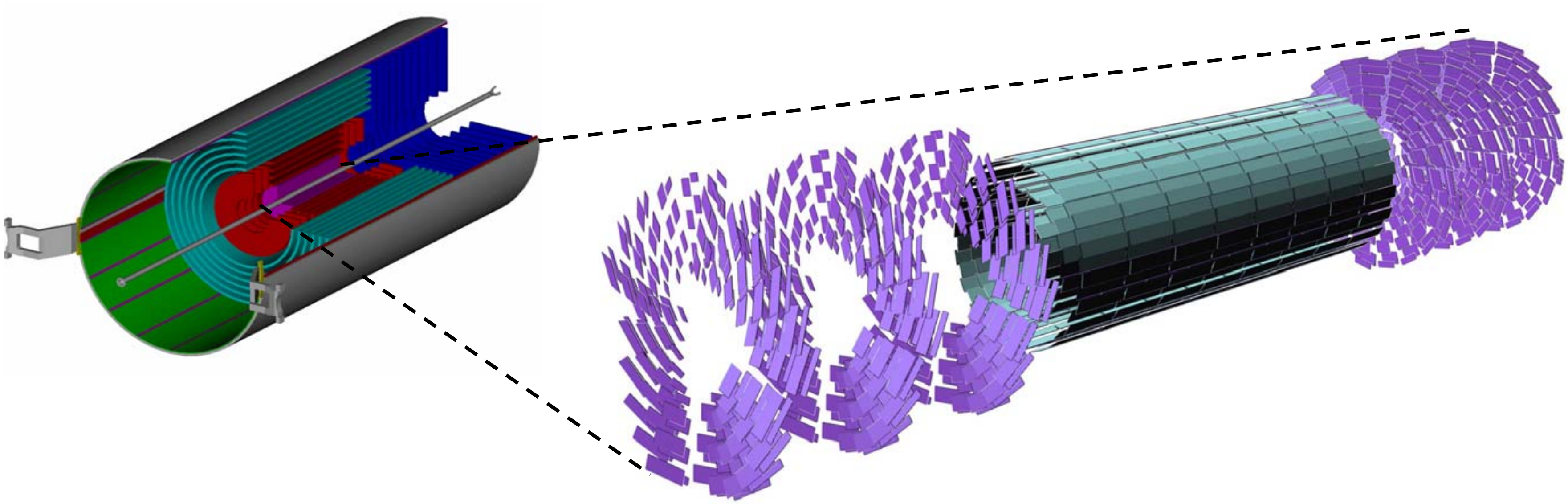


CMS SST: Integration





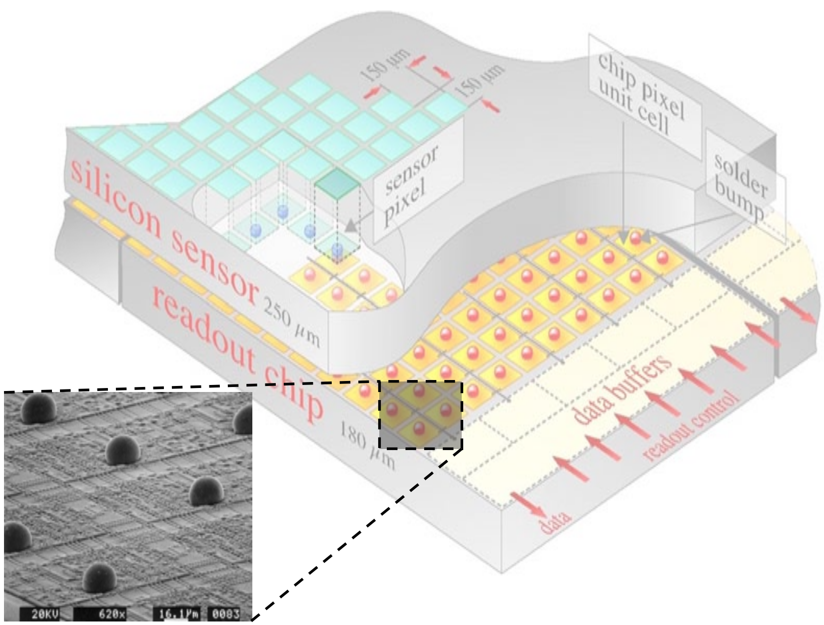
CMS Pixel detector

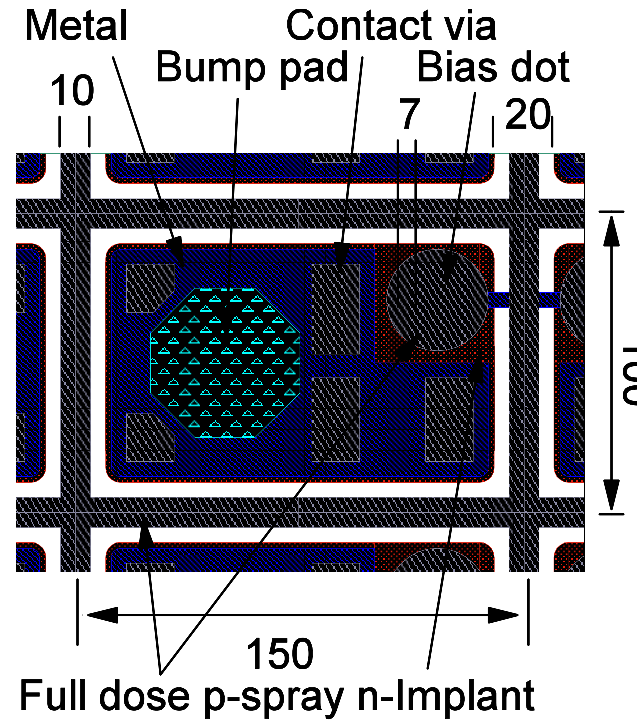


- Hybrid pixel technology
- 3-d tracking with about 66 million channels
- Barrel layers at radii = 4.3cm, 7.2cm and 11.0cm
- Pixel cell size = 100x150 μm^2
- 704 barrel modules, 96 barrel half modules, 672 endcap modules
- ~15,000 front-end chips and ~1m^2 of silicon

CMS Pixel sensors

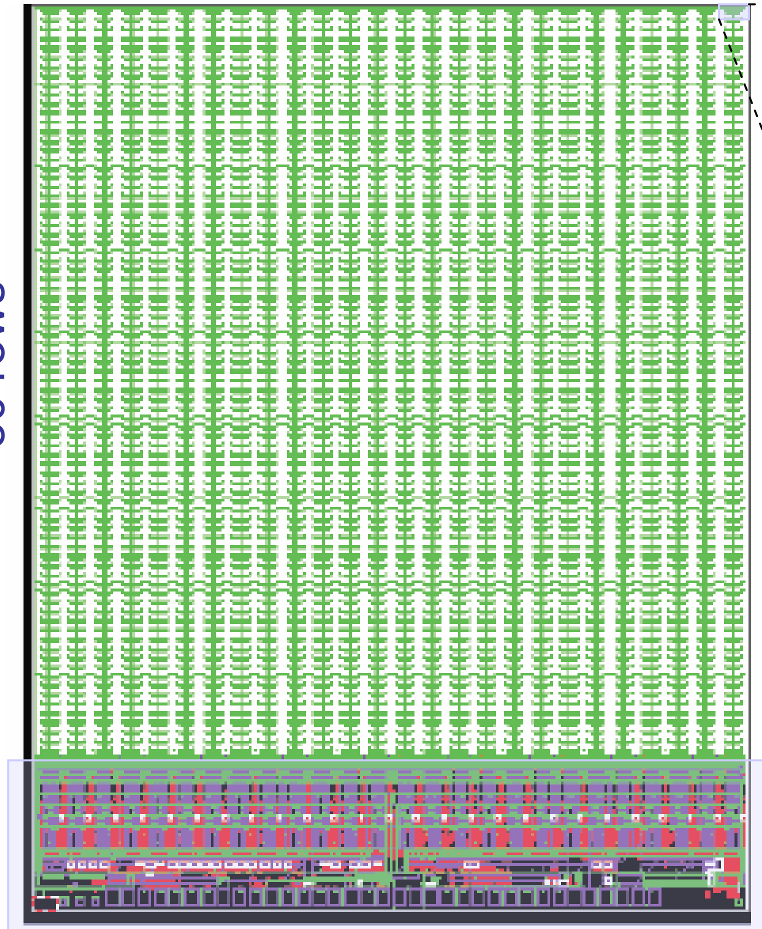
Hybrid pixel detector
Each pixel cell is bump-bonded to its own front end circuit

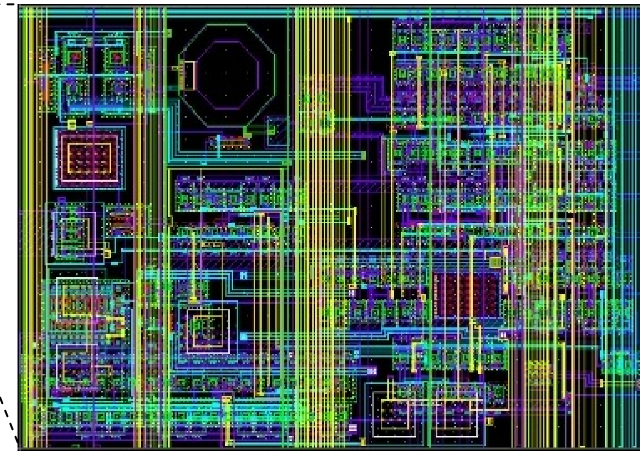




- *n*-in-*n* type with moderated p-spray isolation
- biasing grid and punch through structures (keeps unconnected pixels at ground potential, I-V tests possible)
- 285 μm thick <111> DOFZ wafer

CMS Pixel readout chip





Pixel readout chip

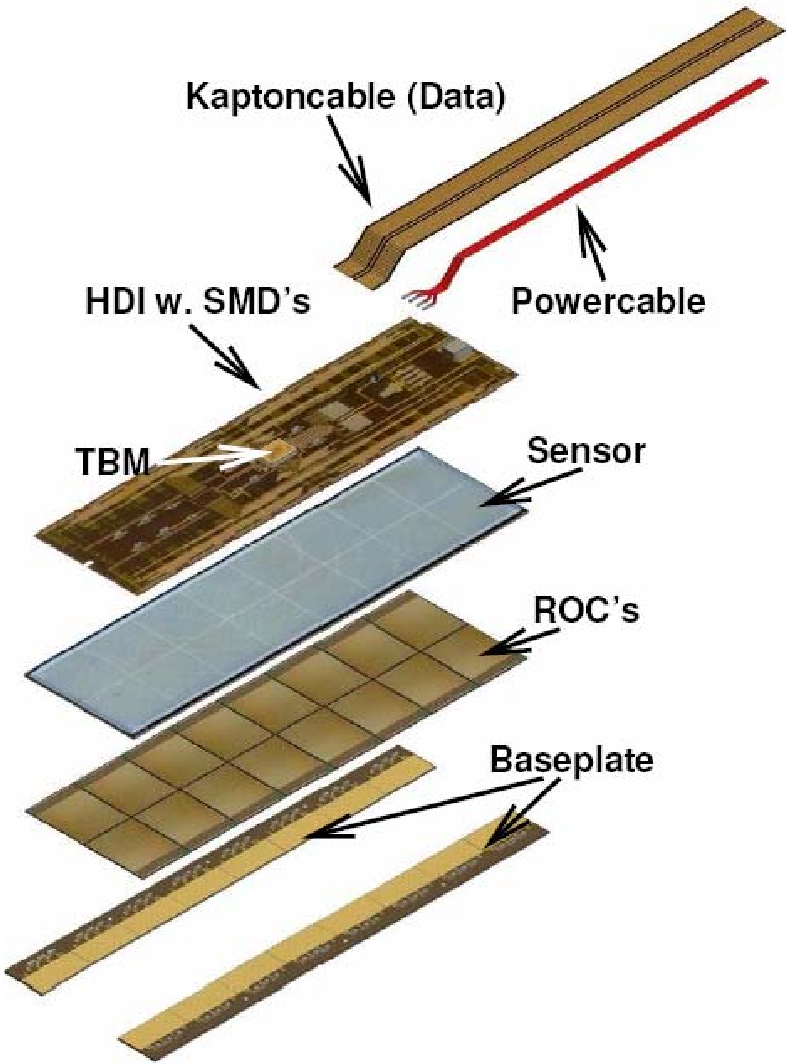
0.25 μm CMOS

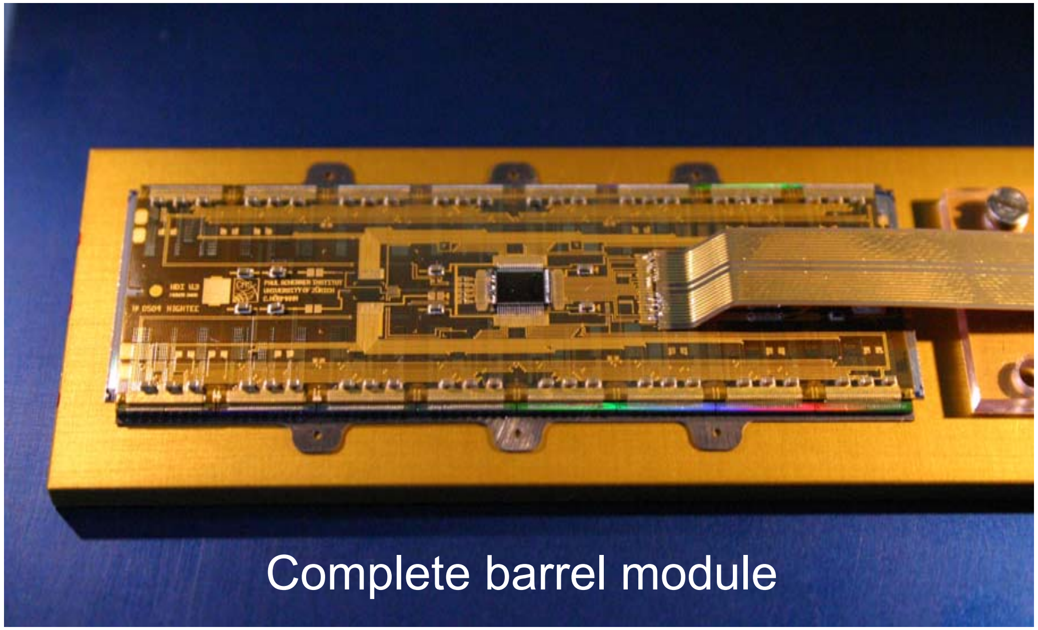
Each readout cell contains:

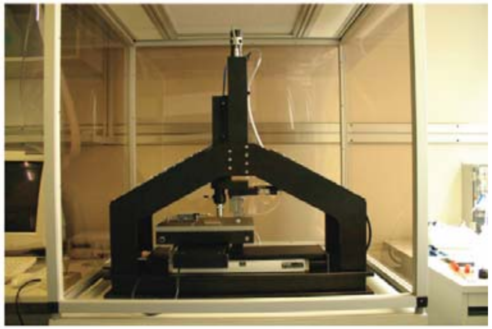
- Charge amplifier
- Shaper
- Programmable discriminator
- Storage capacitor

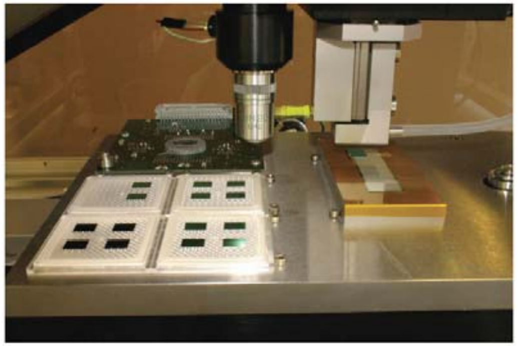
Pixel above threshold transferred to periphery with timestamp+address

CMS Pixel modules







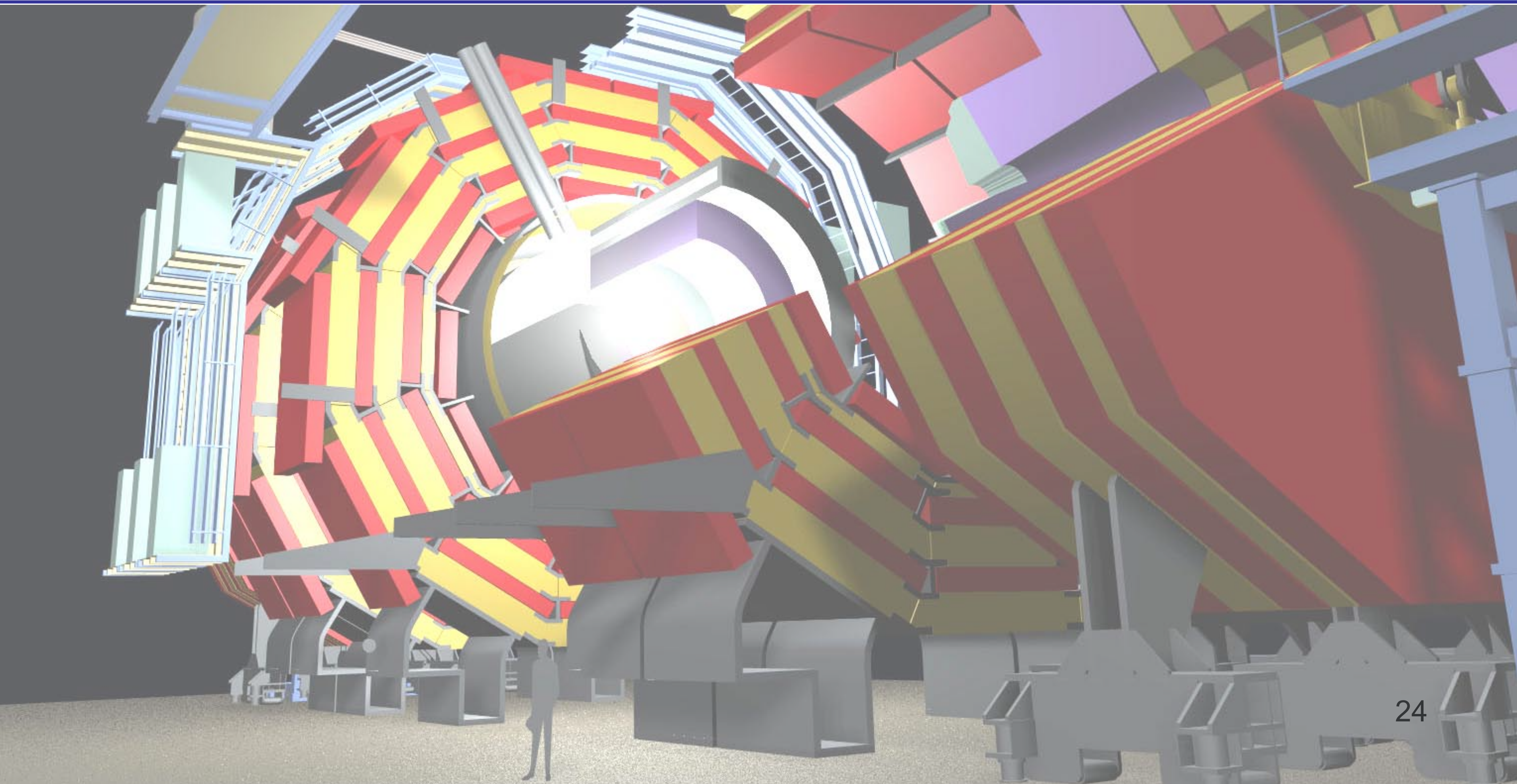


Automatic bump bonding in-house at PSI

CMS Tracker: Status and plans

- Priorities for 2006:
  - Complete integration and commissioning of the Tracker at CERN
  - Magnet test and cosmic challenge: CMS slice test with cosmics
  - 25% System test
- HW Status:
  - TIB+/TID+ integration in Italy in very good shape.
  - TEC+ integration in Aachen started (first sector of 18 petals completed)
  - TOB integration planned to start at CERN (week 9). TOB module construction completed at FNAL.
  - Pixels: start barrel module production May 06. Mechanical support structures for 2007 pilot run ready by end 06.
- SW plans:
  - Software for magnet test fully commissioned by April 06
  - Software for 25% system test fully commissioned by June 06

Performance degradation after irradiation

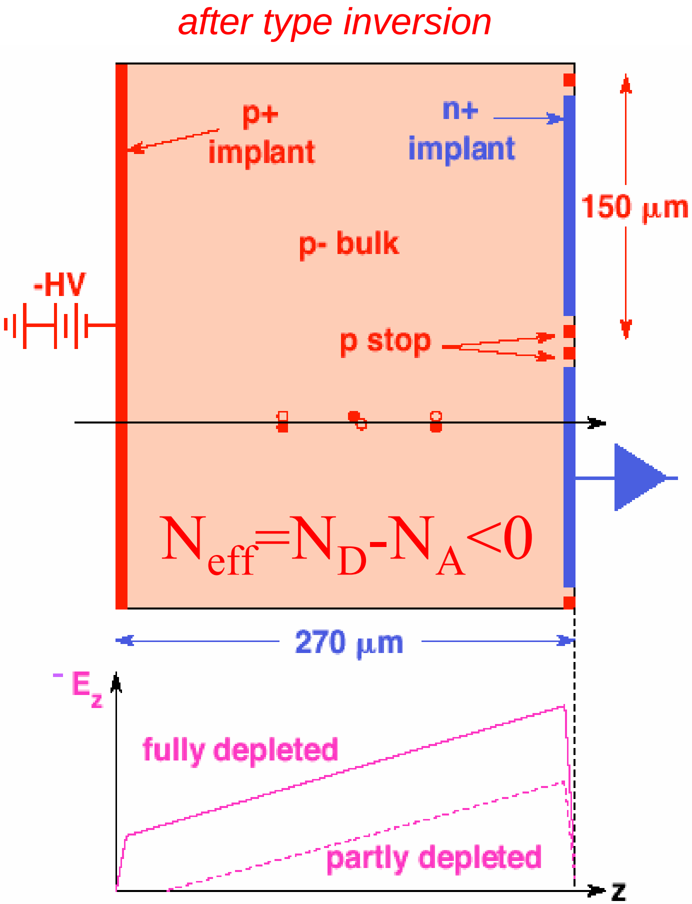


Silicon detector operation at LHC

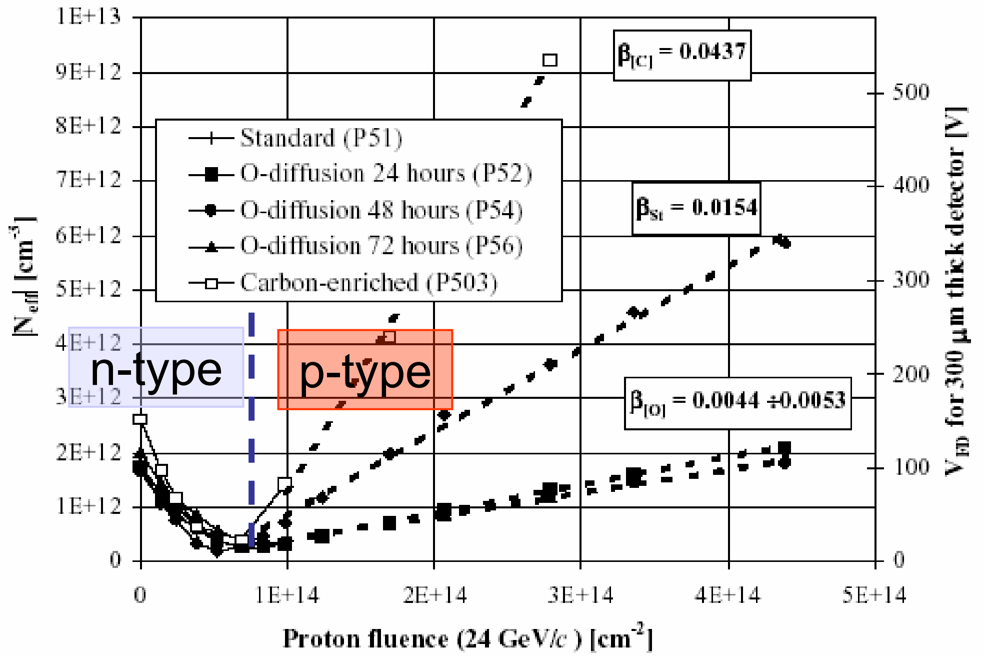
- "Assembled and installed detector" does not mean "ready for physics"!
- Detector commissioning and calibration software development is a very delicate phase where detectors experts and sw developers must collaborate and share know-how.
- Calibration of a silicon detector involves e.g.:
  - Pedestals, tune thresholds, spot noisy or dead channels
  - Charge collection efficiency and trapping
  - Lorentz angle, alignment etc.
- The physical properties of a silicon detector will change under heavy irradiation. Calibrations must be kept up-to-date.

- A "case study": CMS pixels (similar case for LHC strip detectors but lower fluence, no oxygenation)

Type inversion



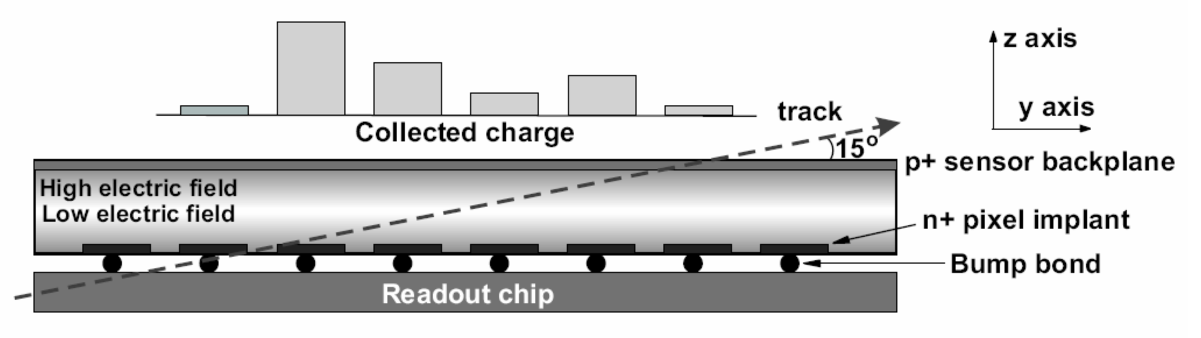
- After irradiation the sensor bulk becomes more acceptor-like
- The space charge density is constant and negative across the sensor thickness
- The p-n junction moves to the pixel implants side
- Sensors may be operated in "partial depletion"



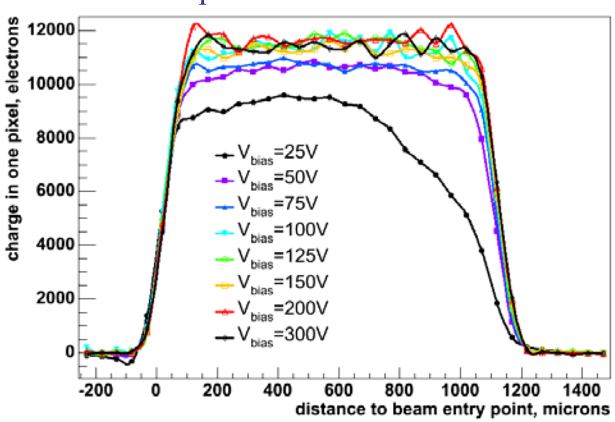
Based on C-V measurements!
…is all this really true?

Charge collection measurements

Charge collection was measured using cluster profiles in a row of pixels illuminated by a 15º beam and no magnetic field

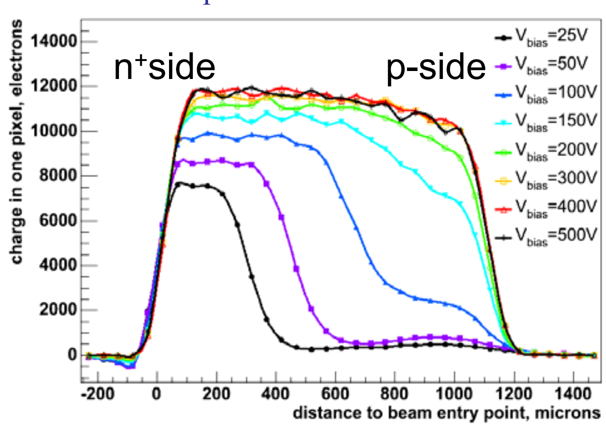


$\Phi_{eq} = 5\times10^{13}$ n/cm^2



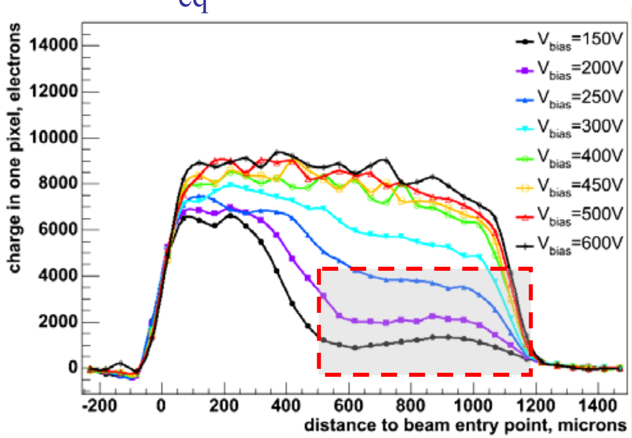
½ year LHC low luminosity

$\Phi_{eq} = 2\times10^{14}$ n/cm^2



2 years LHC low luminosity

$\Phi_{eq} = 6\times10^{14}$ n/cm^2

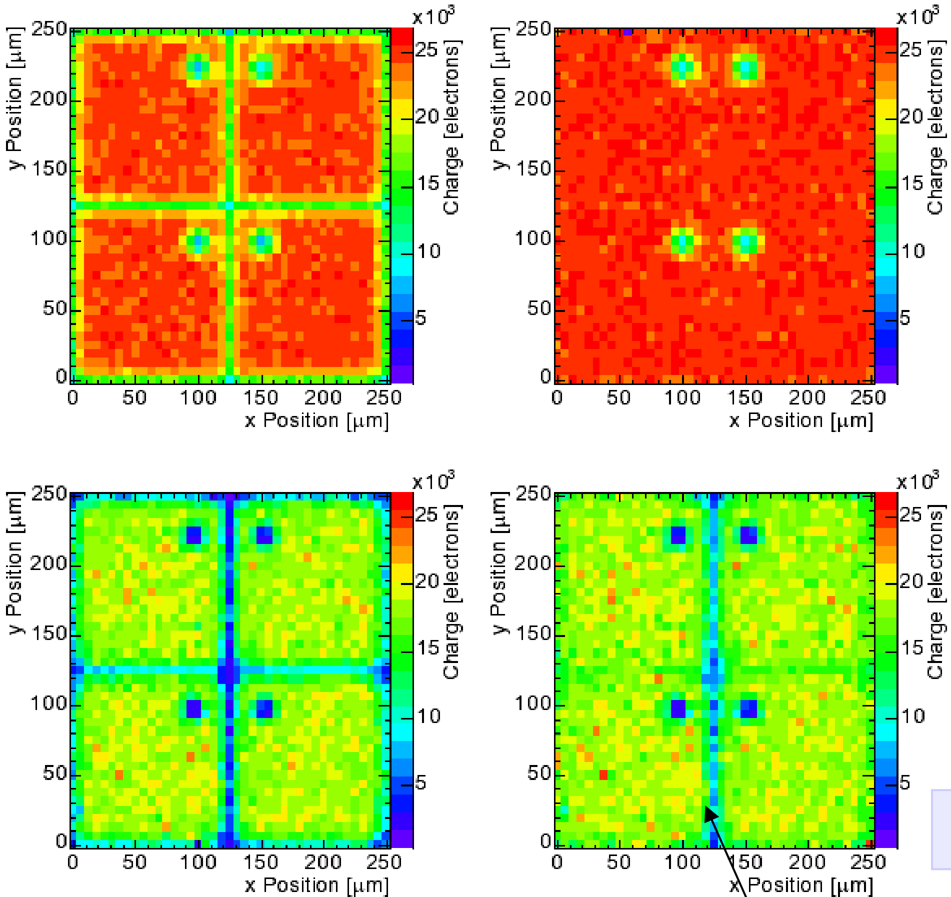


2 years LHC high luminosity

AGEING

Hit detection efficiency

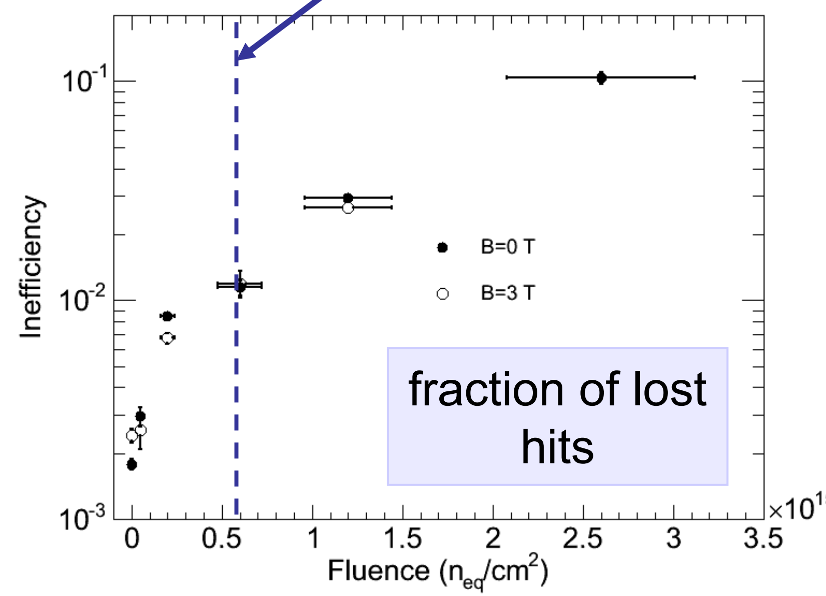
hit pixel   cluster sum



Charge losses below metal biasing grid

unirradiated

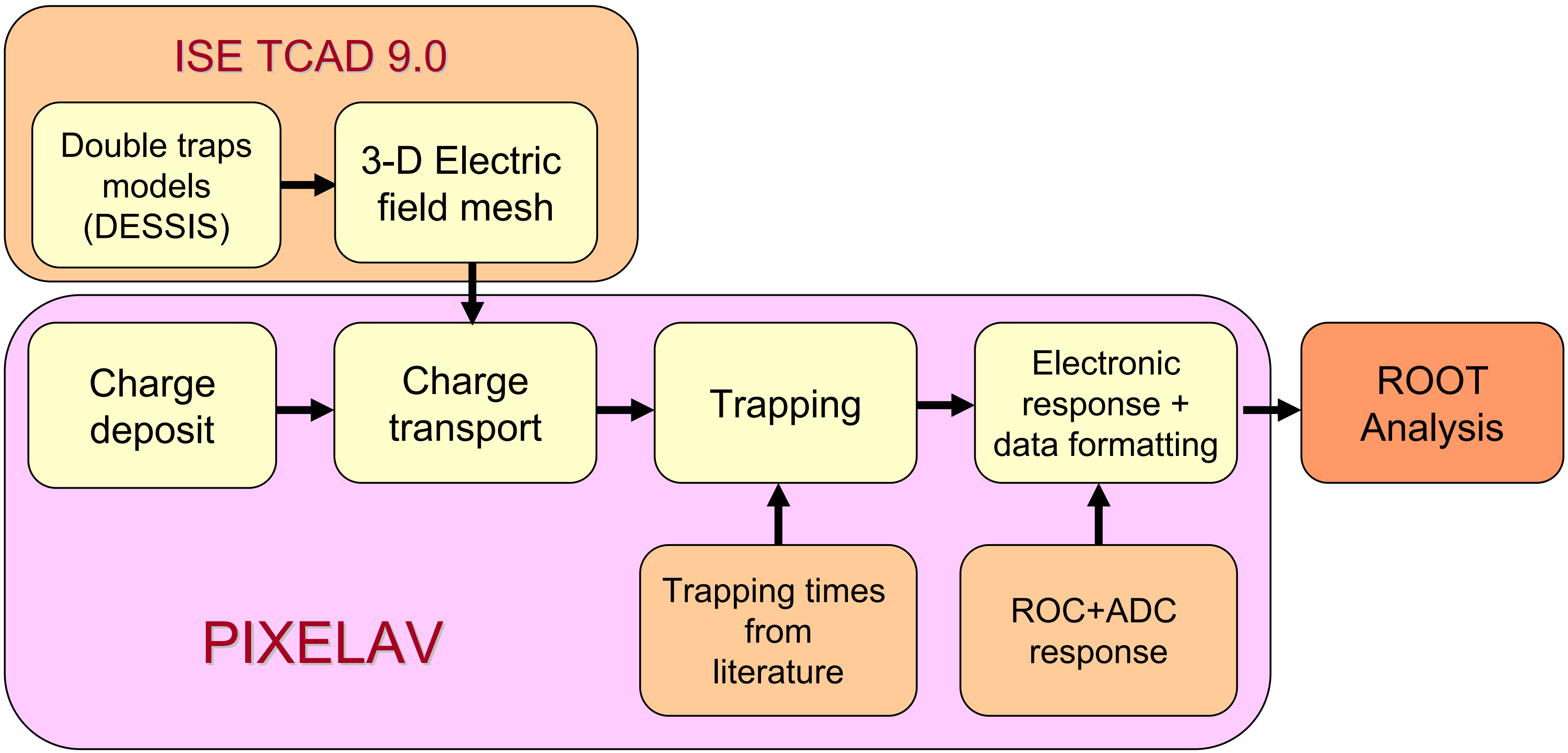
specified radiation hardness



fraction of lost hits

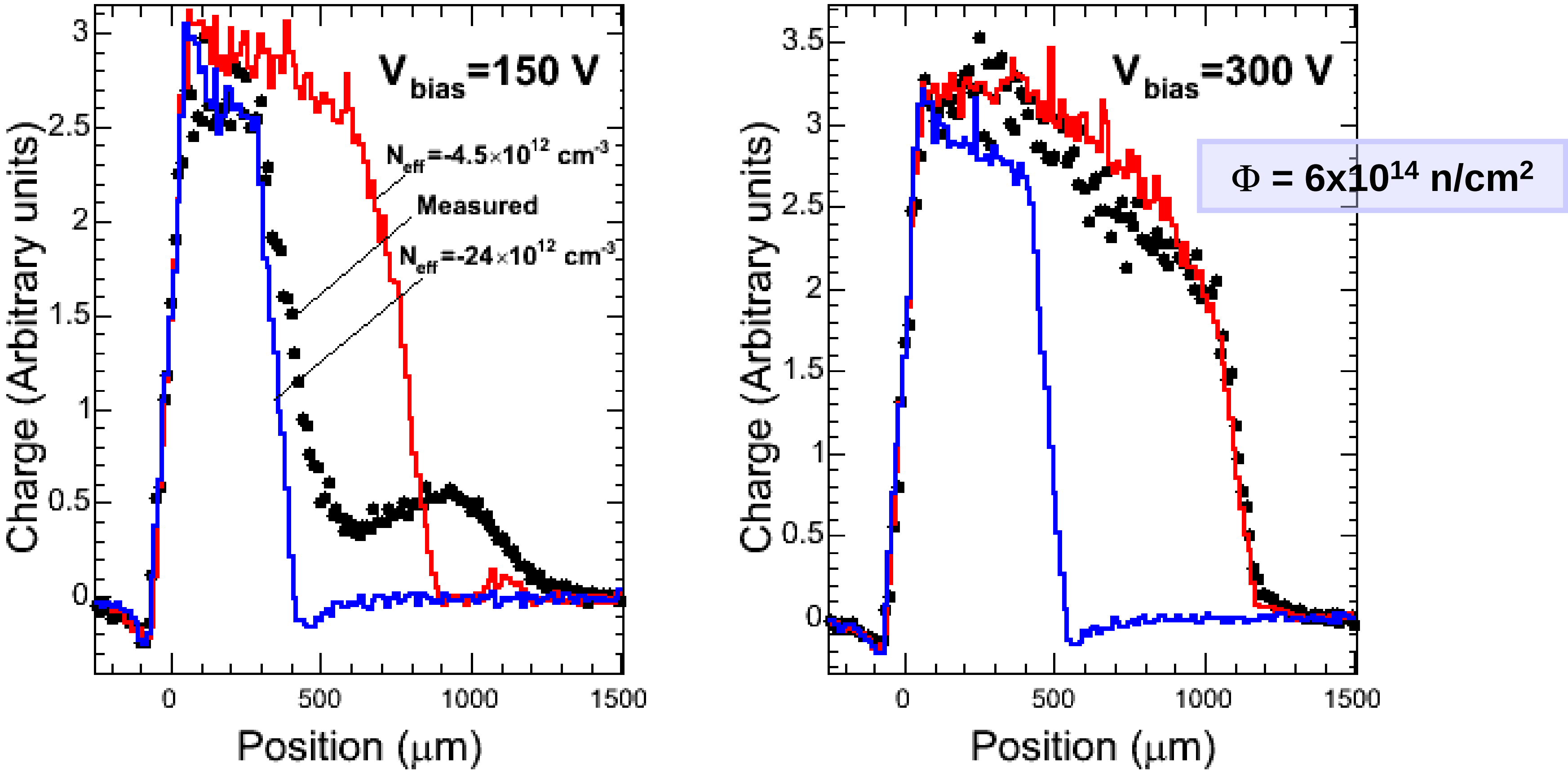
$\Phi = 6x10^{14}$ n/cm2

Detector simulation



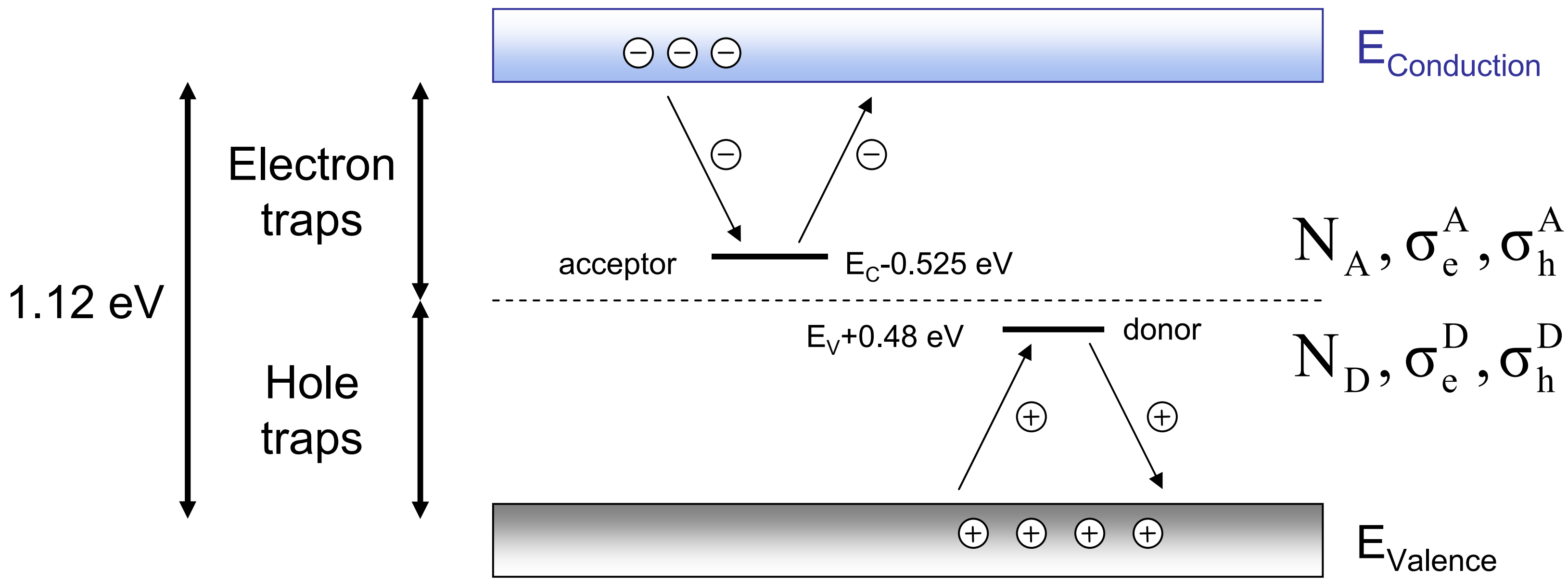
M.Swartz, *Nucl.Instr. Meth*. A511, 88 (2003);
V.Chiochia, M.Swartz et al., *IEEE Trans.Nucl.Sci*. 52-4, p.1067 (2005).

Models with constant N_{eff}



A model based on a type-inverted device with constant space charge density across the bulk does not describe the measured charge collection profiles

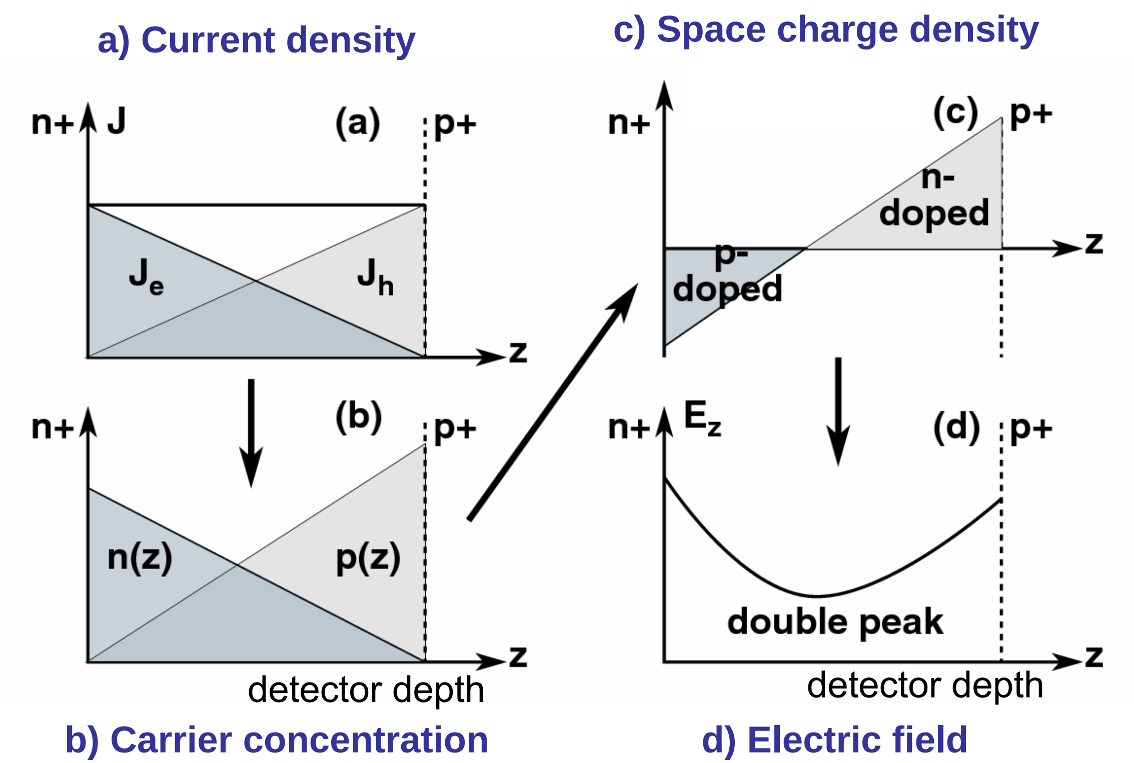
Two-traps effective models

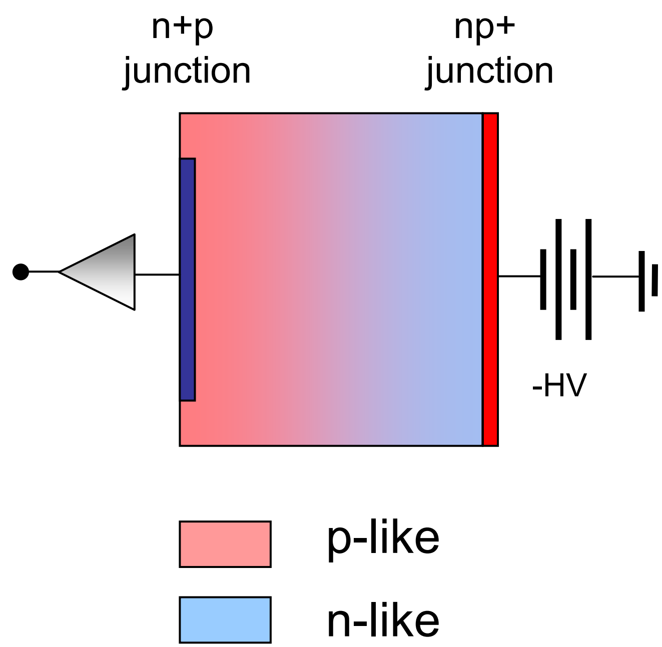


Model parameters (Shockley-Read-Hall statistics):

$E_{A/D}$	= trap energy level	fixed
$N_{A/D}$	= trap densities	extracted from fit
$\sigma_{e/h}$	= trapping cross sections	extracted from fit

The double peak electric field





There are P-N junctions at both sides of the detector

V.Eremin *et al.*, NIM A 476 (2002) p476, NIM A 476 (2002) p537

Model constraints

- Idea: extract model parameters from a fit to the data
- The two-trap model is constrained by:
  1. Comparison with the measured charge collection profiles
  2. Signal trapping rates varied within uncertainties

$$Q_{e,h}(t) = Q_{0e,h} \exp\left(-\frac{1}{\tau_{e/h}} t\right)$$

$$\Gamma_e = 1/\tau_e = \beta_e \Phi_{eq} \cong v_e \sigma_e^A N_A$$

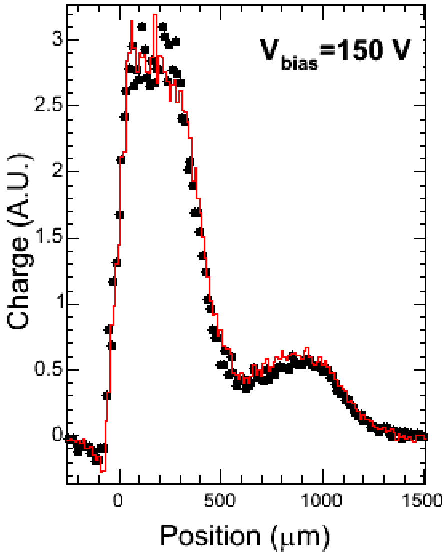
$$\Gamma_h = 1/\tau_h = \beta_h \Phi_{eq} \cong v_h \sigma_h^D N_D$$

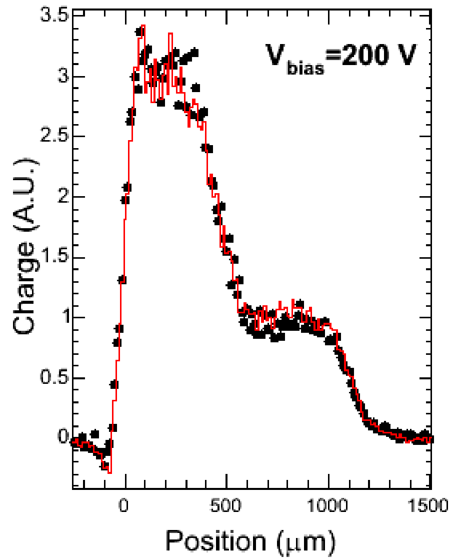
  3. Measured dark current

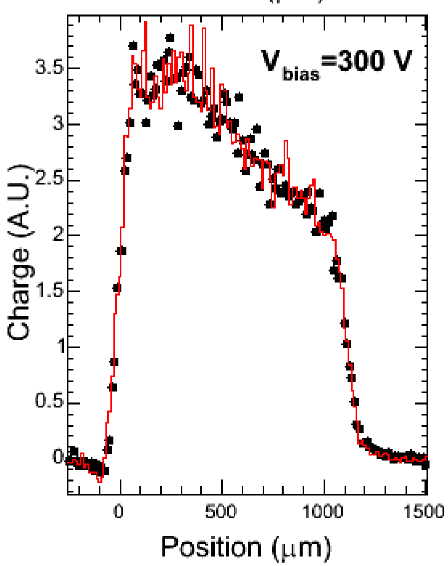
$$I = \sum_{j=D,A} \frac{v_h v_e \sigma_h^j \sigma_e^j N_D (np - n_i^2)}{v_e \sigma_e^j (n + n_i e^{E_j/kT}) + v_h \sigma_h^j (p + n_i e^{-E_j/kT})}$$

Typical fit iteration: (8-12h TCAD) + (8-16h PIXELAV)xV_{bias} + ROOT analysis

Fit results



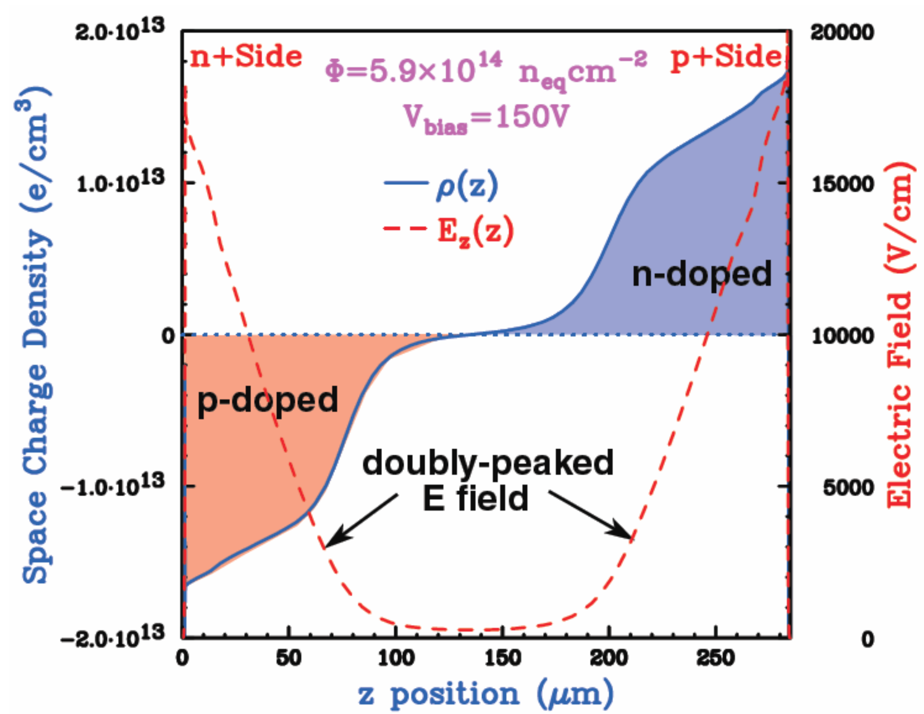




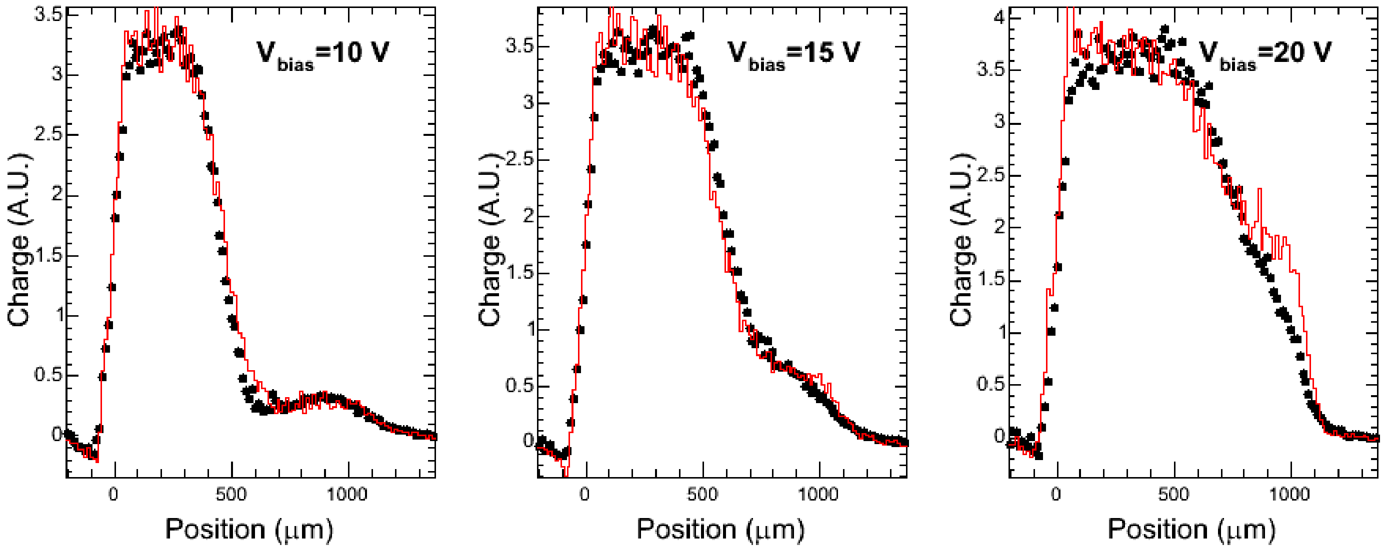
Φ_1=6x10^{14} n/cm^2
N_A/N_D=0.40
σ_h/σ_e=0.25

- ● Data
- — Simulation

Electric field and space charge density profiles

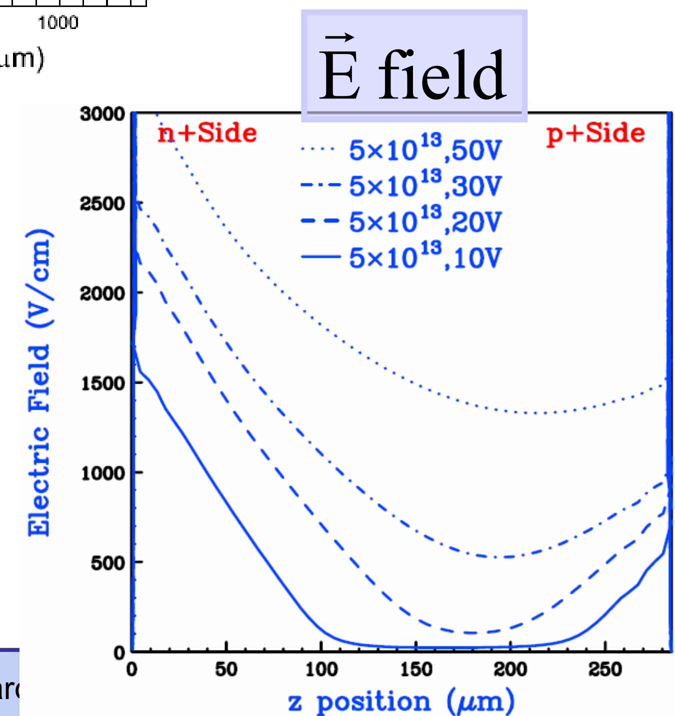


Scaling to lower fluences

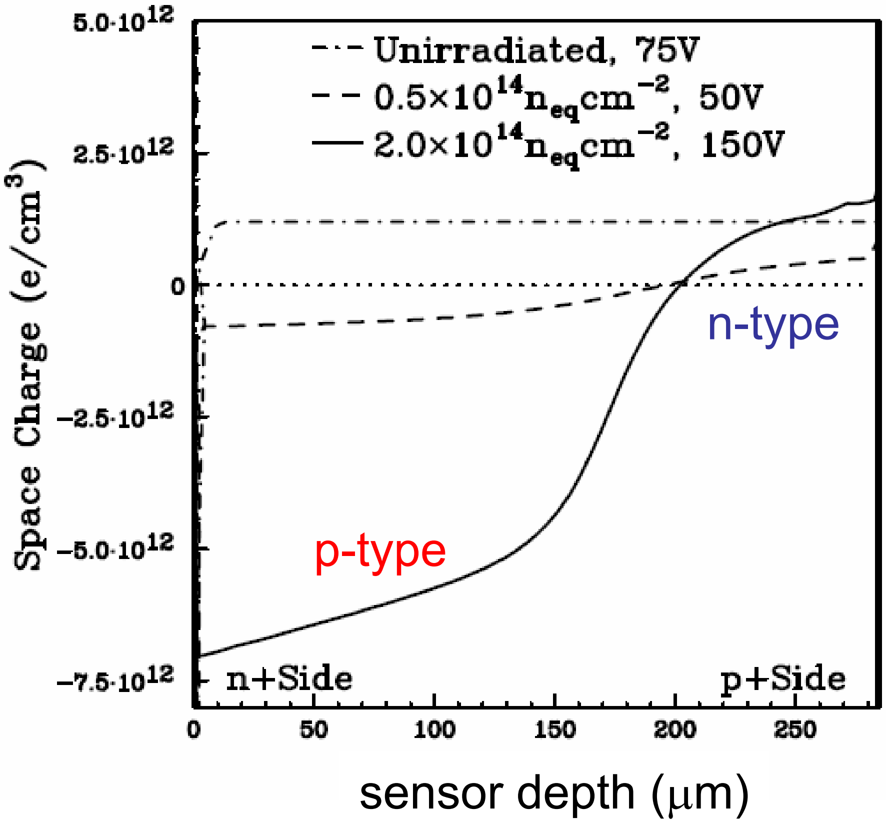


Φ_3=0.5x10^{14} n/cm^2
N_A/N_D=0.75
σ^A_h/σ^A_e=0.25
σ^D_h/σ^D_e=1.00

- Near the 'type-invesion' point: the double peak structure is still visible in the data!
- Profiles are not described by thermodynamically ionized acceptors alone
- At these low bias voltages the drift times are comparable to the preamp shaping time (simulation may be not 100% reliable)



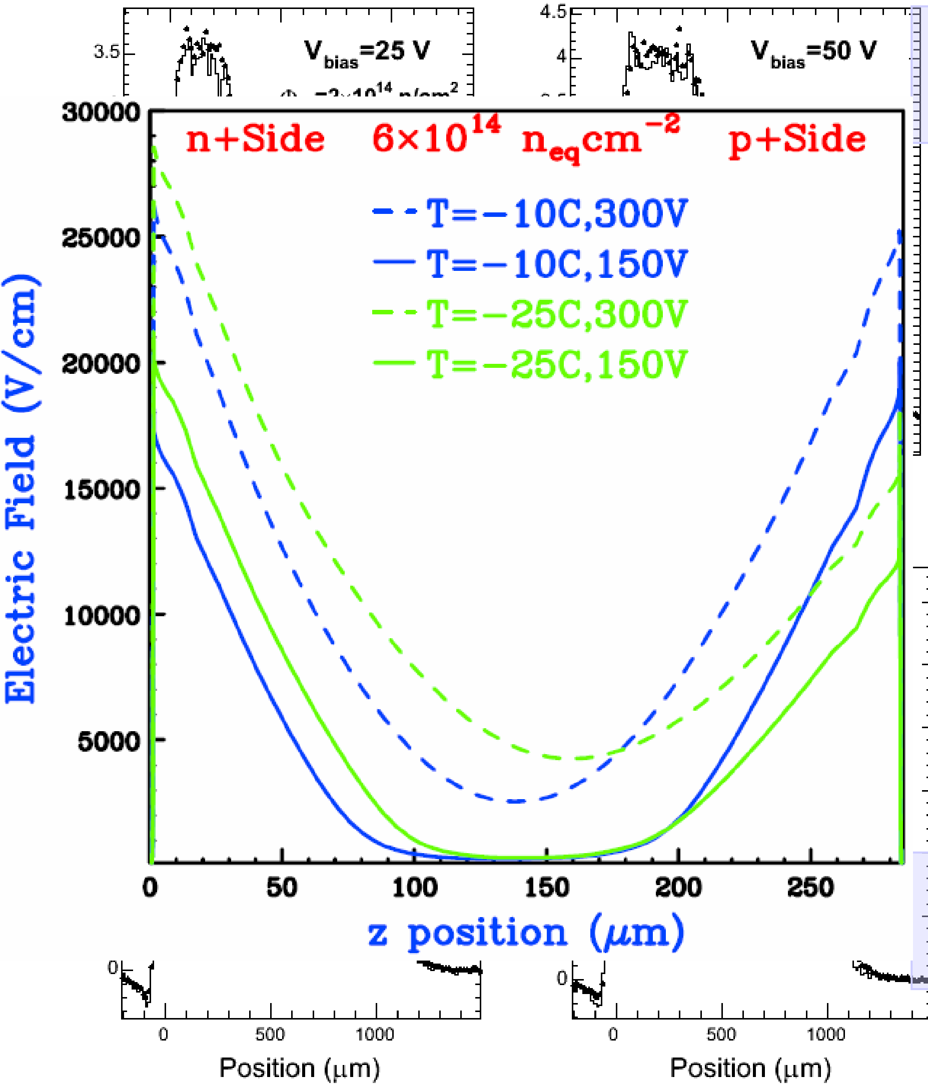
Space charge profile



V.Chiochia, M.Swartz,et al.,physics/0506228

- Space charge density uniform before irradiation
- Current conservation and non uniform carrier velocities produce a non linear space charge density after irradiation
- The electric field peak at the p+ backplane increases with irradiation

Temperature dependence



Φ_2=2x10^{14} n/cm^2
T=-25º C

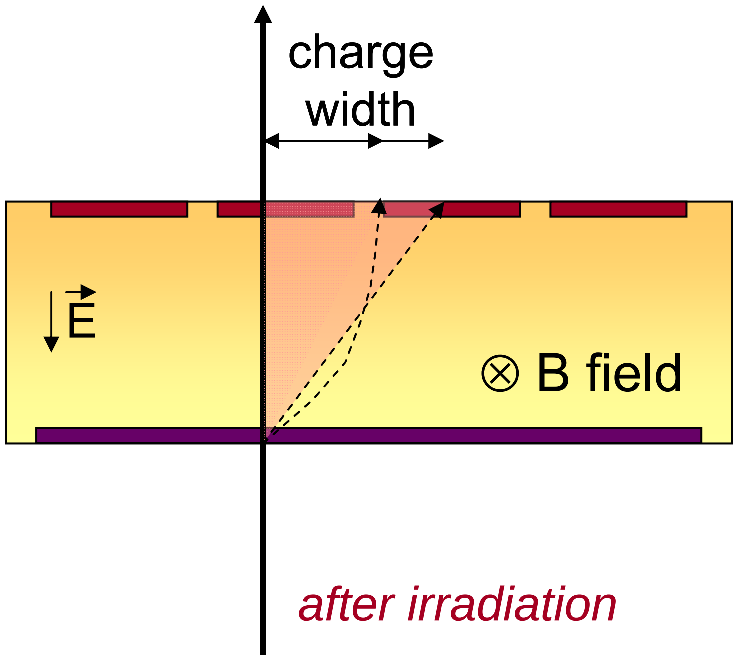
Φ_1=6x10^{14} n/cm^2
T=-25º C

- Comparison with data collected at lower temperature T=-25º C.
- Use temperature dependent variables:
  - recombination in TCAD
  - variables in PIXELAV
- The double-trap model is predictive!

V.Chiochia, M.Swartz,et al., physics/0510040

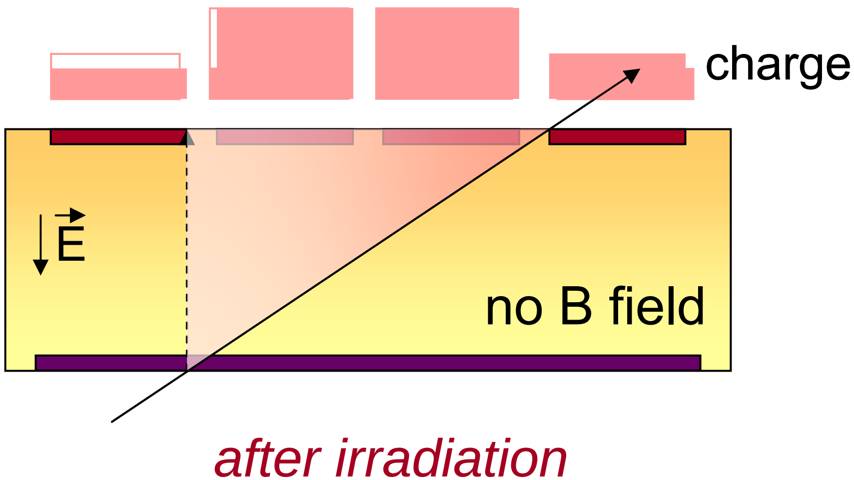
Impact on reconstruction

r-ϕ plane



Irradiation modifies
the electric field profile:
varying Lorentz deflection

r-z plane

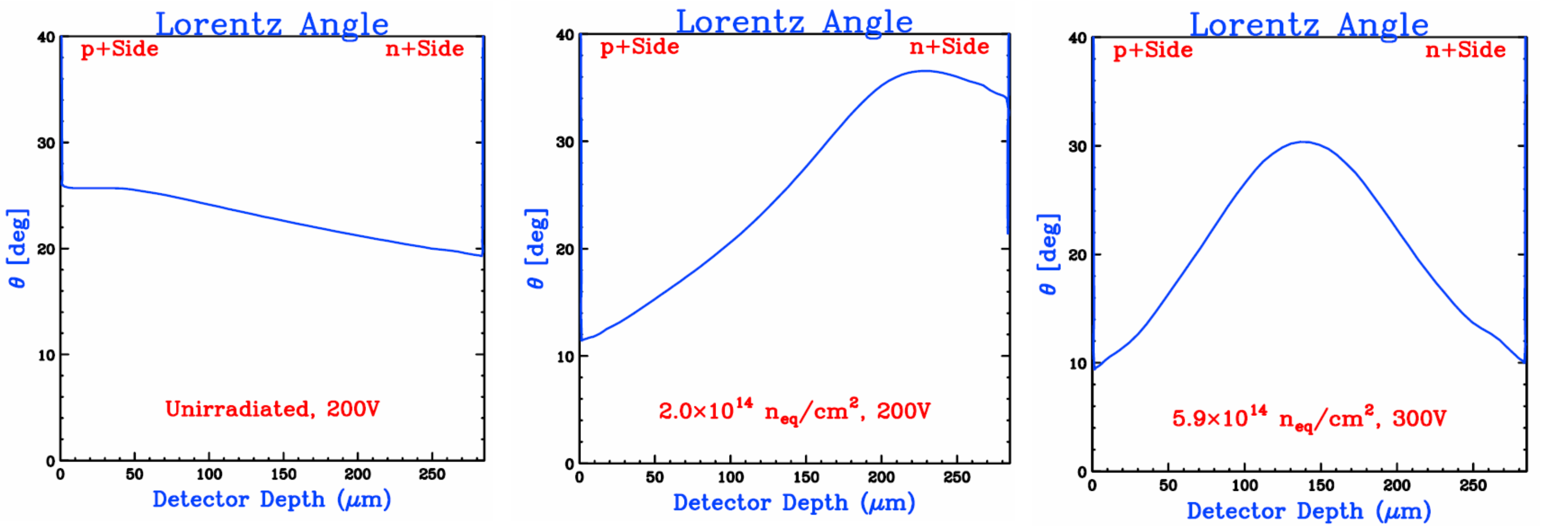


Irradiation causes
charge carrier trapping

Lorentz deflection

Switching on the magnetic field:

tan(θ) linear in the carrier mobility μ(E): $\tan\theta_L = r_H \mu(\vec{E}) B \sin\theta_{vB}$

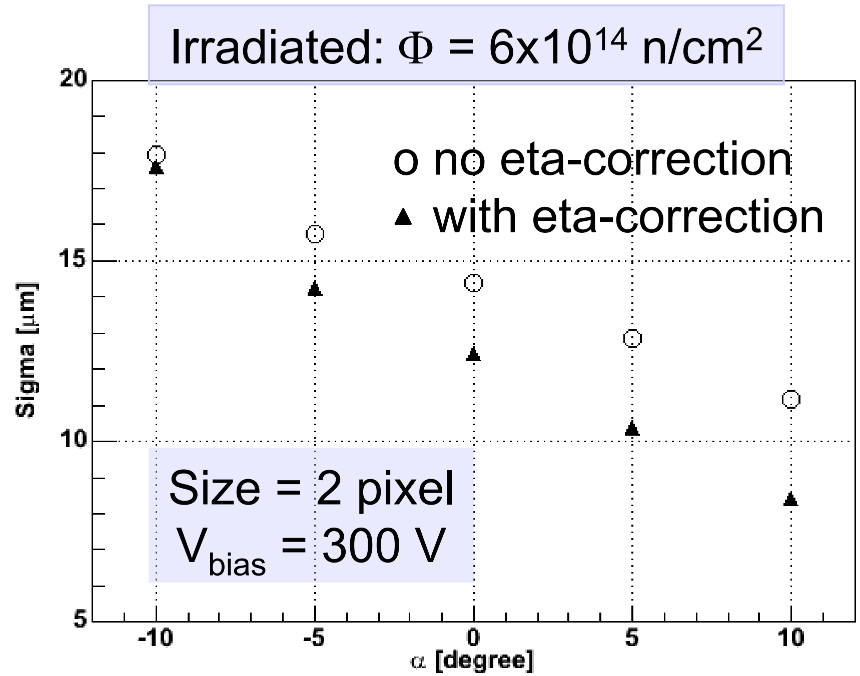


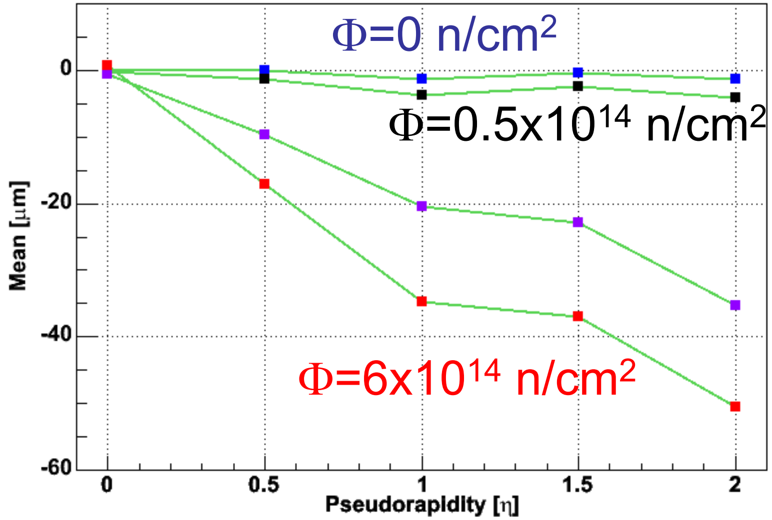
LHC startup | 2 years LHC low luminosity | 2 years LHC high luminosity

The Lorentz angle can vary a factor of 3 after heavy irradiation:
This introduces strong non-linearity in charge sharing

Position resolution

- Position resolution along the r-ϕ coordinate from simulation
- Pitch = 100 μm, Lorentz effect
- Before irradiation:
  - Size = 2, α=0° $\rightarrow$ $\sigma \sim 9$ μm
- After irradiation (6×10^{14} n/cm^2)
  - Size = 2, α=0° $\rightarrow$ $\sigma \sim 12$ μm
- Eta corrections can improve resolution after irradiation!





- z (longitudinal) coordinate: residuals mean along the z coordinate vs. pseudorapidity
- Large systematic shifts after irradiation!

E.Alagöz et al., physics/0512027

Summary

- After heavy irradiation trapping of the leakage current produces electric field profiles with two maxima at the detector implants. The space charge density across the sensor is not uniform, only ~half of the junction type-inverts.
- What is the meaning of V_{dep}, depletion depth and type inversion? Measurements reflecting the electric field profile (e.g. TCT, CCE, long clusters etc.) are preferable to C-V characterization to understand radiation damage in running detectors
- A physical model based on two defect levels can describe the charge collection profiles measured with irradiated pixel sensors in the whole range of irradiation fluences relevant to LHC operation
- Our model is an "effective theory": e.g. in reality there are several trap levels in the silicon band gap after irradiation. However, it is suited for calibration and software development related to silicon detectors at LHC.
- We are currently using the PIXELAV simulation to develop hit reconstruction algorithms and calibration procedures optimized for irradiated pixel sensors.

References

- PIXELAV simulation:
  - M.Swartz, "CMS Pixel simulations", *Nucl.Instr.Meth*. A511, 88 (2003)
- Double-trap model:
  - V.Chiochia, M.Swartz et al., "Simulation of Heavily Irradiated Silicon Pixel Sensors and Comparison with Test Beam Measurements", *IEEE Trans.Nucl.Sci*. 52-4, p.1067 (2005), eprint:physics/0411143
  - V. Eremin, E. Verbitskaya, and Z. Li, "The origin of double peak electric field distribution in heavily irradiated silicon detectors", *Nucl. Instr. Meth.* A476, pp. 556-564 (2002)
- Model fluence and temperature dependence:
  - V.Chiochia, M.Swartz et al., "A double junction model of irradiated pixel sensors for LHC", accepted for publication on *Nucl. Instr. Meth.A,* eprint:physics/0506228
  - V.Chiochia, M.Swartz et al., "Observation, modeling, and temperature dependence of doubly-peaked electric fields in silicon pixel sensors", Accepted for publication on *Nucl. Instr. Meth.A,* eprint:physics/0510040