Silicon Sensor Development for ATLAS Upgrade for SLHC

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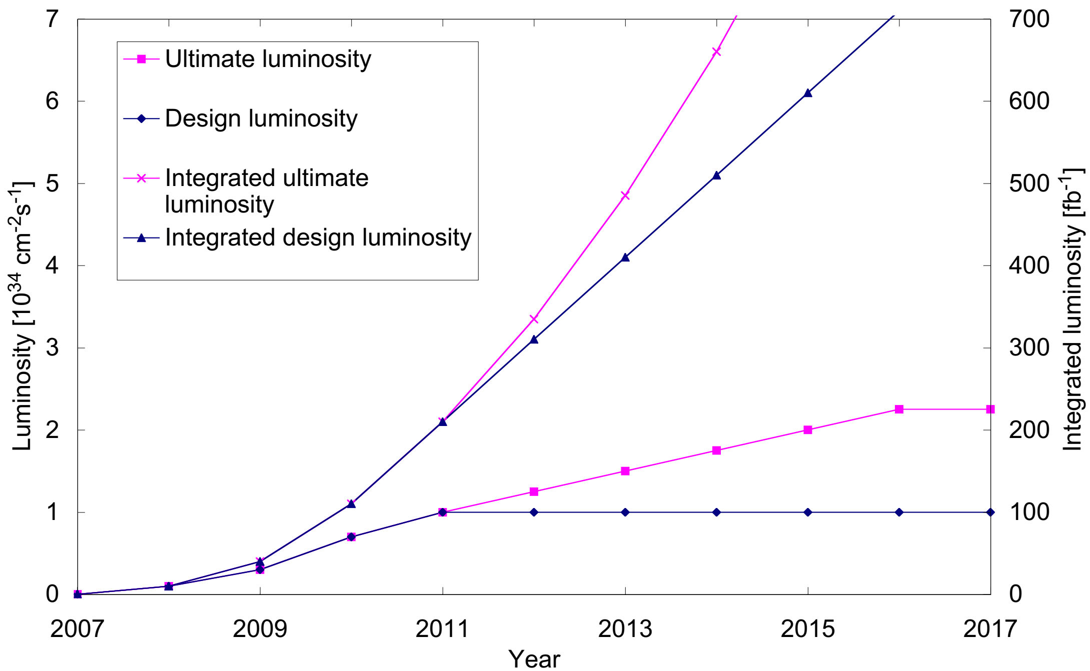
Toward SLHC Upgrade

- In the present LHC
  - Radiation damage limit in IR Q-magnet at ~700 fb^{-1}
  - From the integrated luminosity, IR Q-mag. reaches its life in the end of the year with
  - design luminosity, 2016
  - ultimate luminosity, 2014
    - 1.1->1.7x10^{11} p/bunch
    - limited by beam dumping system



- LHC machine upgrade is foreseen in ~2015 to Super LHC
  - Luminosity upgrade => Phase 1
  - Energy upgrade is too expensive, but …some => Phase 2

Super LHC Luminosity Upgrade

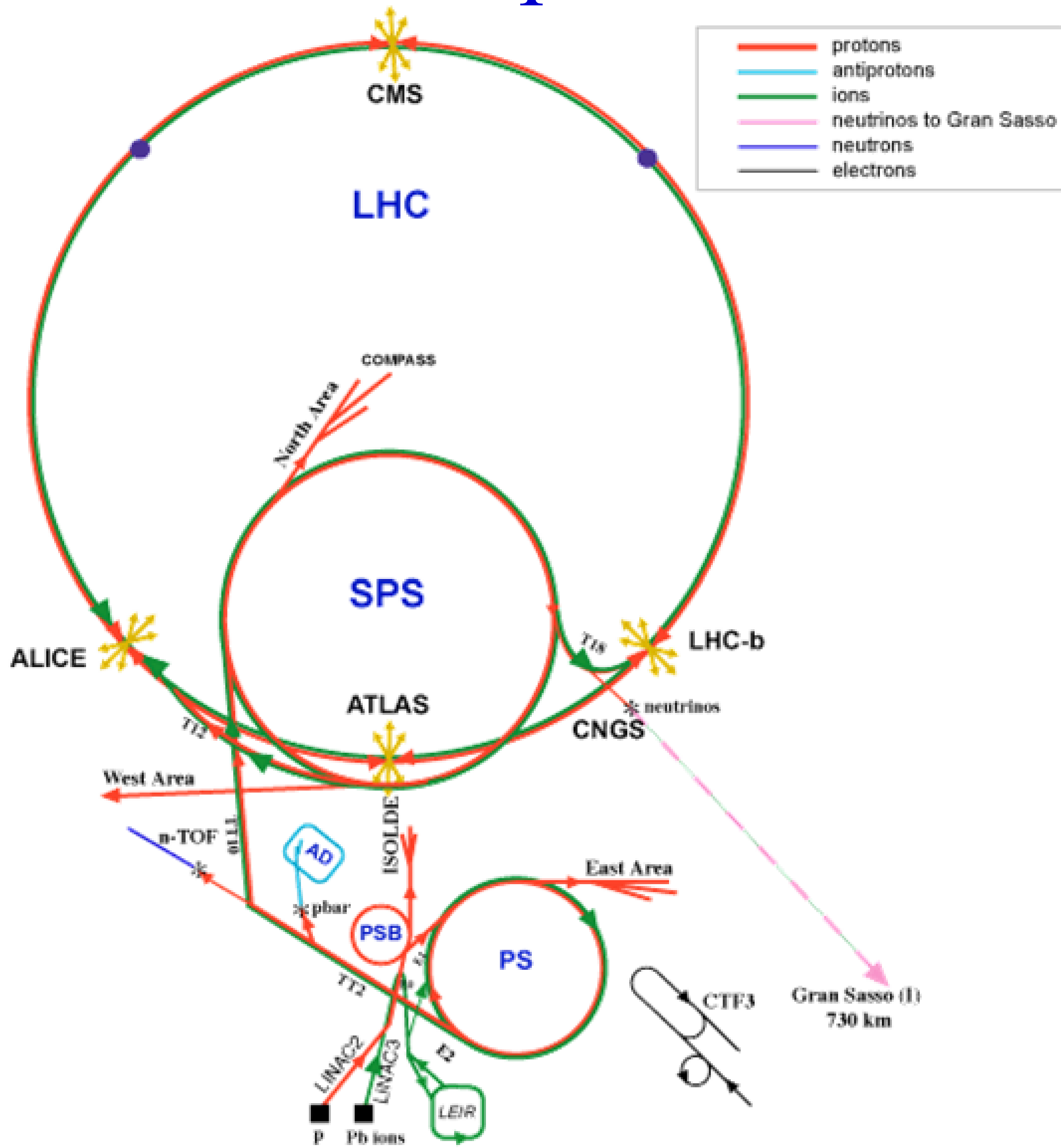
- Phase 1: reach the maximum with IR change and new RF system
  - Increase protons per bunch up to the ultimate intensity => $3.3\text{x}10^{34}$ $cm^{-2}s^{-1}$
    - Modify insertion Q-mag. and/or layout
      - beta* = 0.25 m
    - Increase crossing angle by sqrt(2)
      - $theta_c$ = 445 urad
    - $N_b = 1.7\text{x}10^{11}$ p/bunch
  - Halve rms bunch length with high harmonic RF system => $4.6\text{x}10^{34}$ $cm^{-2}s^{-1}$
    - $sigma_z$ = 3.78cm
    - with new RF system, not cheap
  - Double the number of bunches => $9.\ 2\text{x}10^{34}$ $cm^{-2}s^{-1}$
    - n_b = 5616 bunches, bunch spacing = 12.5 ns
    - Upgrade cryogenics, collimation, dumping system
    - Possibly upgrade SPS RF system and other in injectors

SLHC Luminosity and Energy Upgrade

- Phase 2: Significant changes to injectors, SPS, LHC with new dipoles
  - Injectors and SPS upgrade => factor 2 increase
    - Increase the beam intensity and brilliance beyond its ultimate value
    - Inject into LHC at 1TeV
    - with superconducting magnets, upgraded transfer lines
    - Energy swing reduced by a factor 2 <= a step to energy upgrade
    - Interesting alternative: add low-field booster ring in the LHC tunnel
  - LHC upgrade => 12.5 TeV
    - New dipoles with a field of 15 T
    - could be operated by 2020

CERN Accelerator Complex

- Accelerator chain to LHC
  - LINAC
  - BOOSTER
  - PS
  - SPS
  - LHC
- Others
  - CNGS
    - CERN Neutrino Gran Sasso
  - CTF3
    - CLIC Test Facility 3



Physics Motivations for SLHC

	LHC	SLHC
• Integrated luminosity (ATLAS+CMS)	600 fb^{-1}	6000 fb^{-1}
• Triple Gauge Boson coupling		
– Coupling constants	1	~1/2
• FCNC top decays		
– Branching ratios ($t \to q\gamma$, $\to qg$, $\to qZ$)	1	1/3~1/10
• Higgs coupling to fermions and bosons		
– Ratio (Γ_W/Γ_f) measurement	1	~1/2
• Higgs self coupling		
– Higgs pair production	NA	Possible
• Squark and Sgluon		
– Mass reach	m_q, m_g	m_q, m_g + ~500 GeV/c^2
• SUSY parameters		
– Decay chains	NA	Possible
• Extending coverage of MSSM Higgses		
– Single Higgs discovery limit	m_A	m_A + ~100 GeV/c^2
• Strong $V_L V_L$ scattering		
– $W^+_L W^+_L$ scattering excess	2~3 σ	5~8 σ
– Scalar resonance $Z_L Z_L$ -> 4leptons	NA	Possible
• Extra Gauge Bosons		
– mZ', mW'	~5.5 TeV/c^2	~6.5 TeV/c^2

ATLAS Upgrade

- Prepare for luminosity of 10^{35} $cm^{-2}s^{-1}$
  - Integrated luminosity of 1000 fb^{-1} per year
- Least demanding option: 12.5 ns beam crossing
  - Use 25 ns readout, i.e., same electronics for Muon and Calorimeter systems
  - accumulate 2 bunch crossings per readout
    - No. of pile-up events ~200 at 10^{35} $cm^{-2}s^{-1}$ (LHC: 19 at 10^{34})

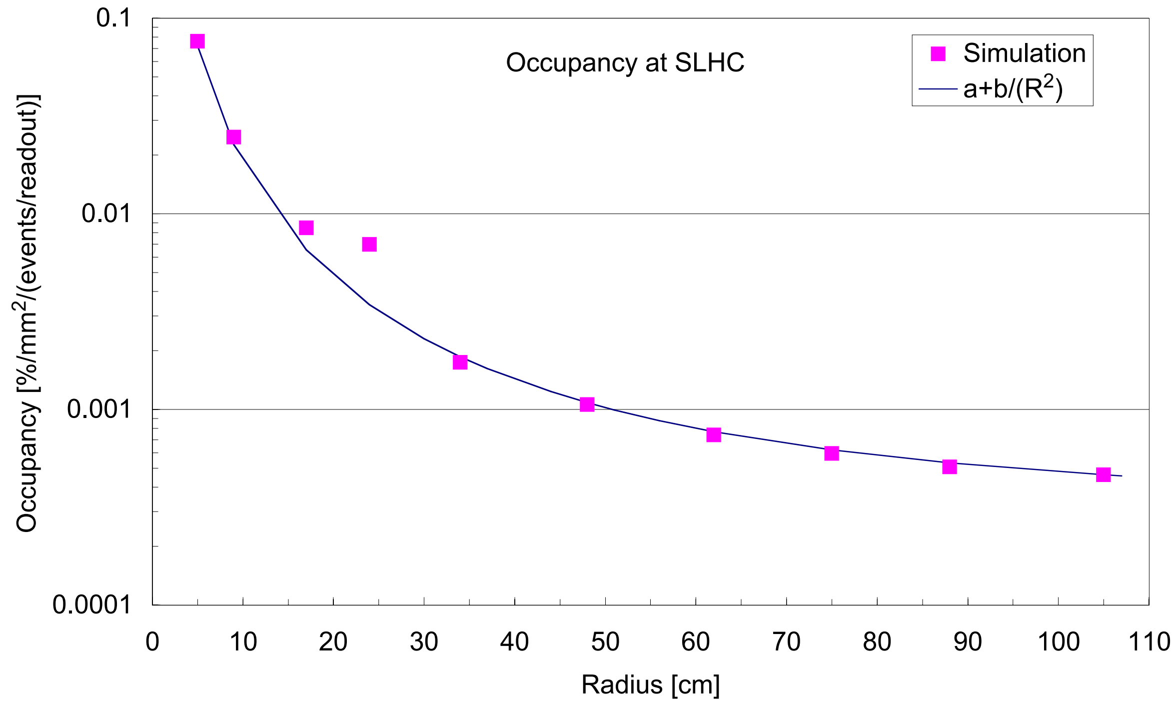
- Trigger (L1) : largely to be replaced
- Muon system: ~OK
  - Reduced η coverage ($|\eta| < 2.0$) to reinforce forward shielding
- Calorimeters: ~OK
  - Pile-up noise ~x3 tolerable
- Inner tracker: to be replaced due to occupancy and radiation fluence
  - TRT -> silicon strips (SCT)
  - SCT -> improved granularity and more radiation tolerant strips (SCT)
  - PIXEL -> more radiation tolerant pixels (PIXEL)
- Physics
  - Similar performance as of LHC

Inner Detector Upgrade

- Luminosity of 10^{35} $cm^{-2}s^{-1}$
  - E.g. Strip sensor design optimization in multi-parameter space
- Integrated luminosity of 3000 fb^{-1}
  - Particle fluence
  - Radiation damages
- Silicon sensors development
  - New PIXEL
  - New SCT

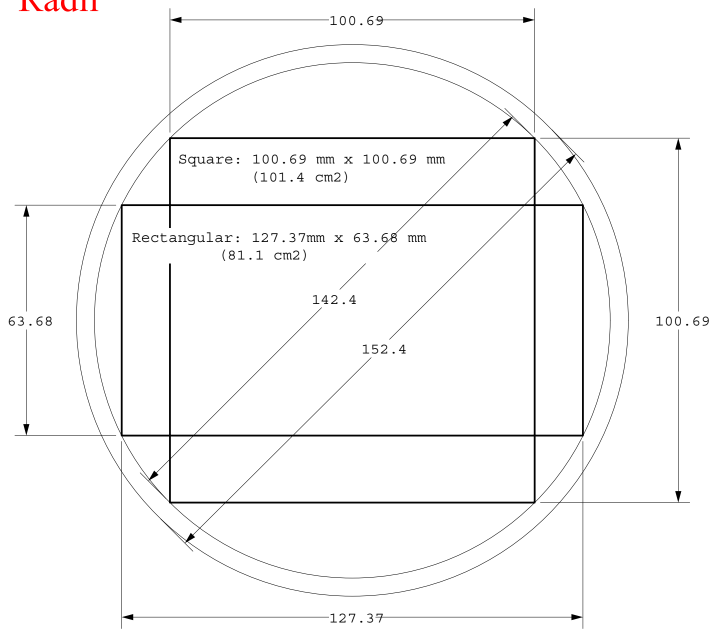
Occupancy

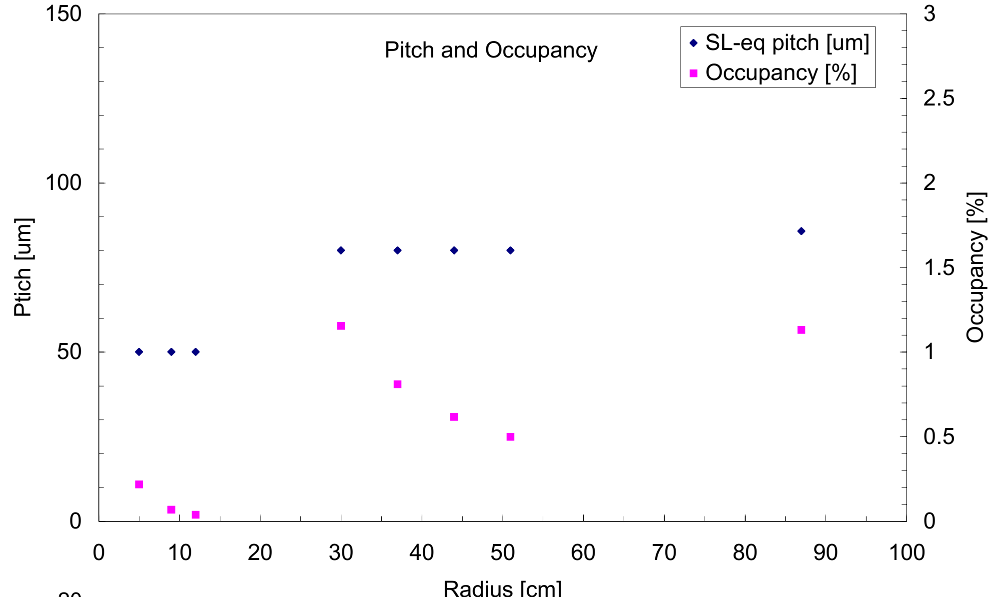
- Scaled occupancy
  - Scaled per area and pile-up events/readout
    - %/mm^2/events
    - Ready for estimation of a case
      - 200 pile-up events
      - Occupancy for an area (= pitch x length) at any radii
  - Based on an occupancies calculation
    - 230 events/per readout
    - Pixels (50um x 400um)
    - Strips (50um x 6cm)
  - Occupancy
    - Mean
    - Typical r.m.s. 50~70%*mean

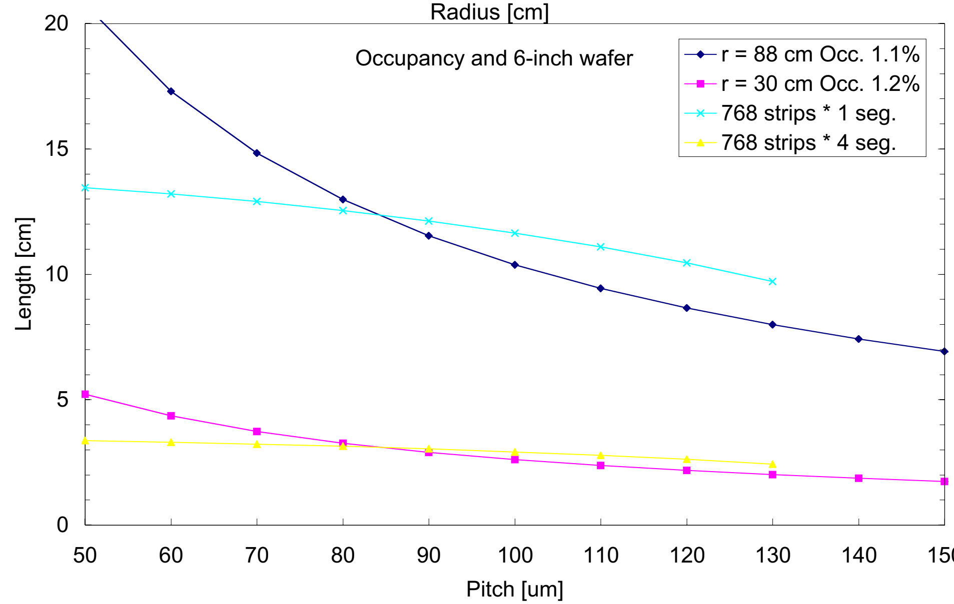


Strip Sensor Design Optimization

- Physics performance
  - e.g. Pitches at Radii
- Occupancy limit (e.g., ~1%)
  - (Pitch*Length) at Radii
- Maximum use of 6-inch Wafer
  - Width (=#strips*pitch)*Length
- Mechanical packaging
  - Width
- Cost
  - Radii

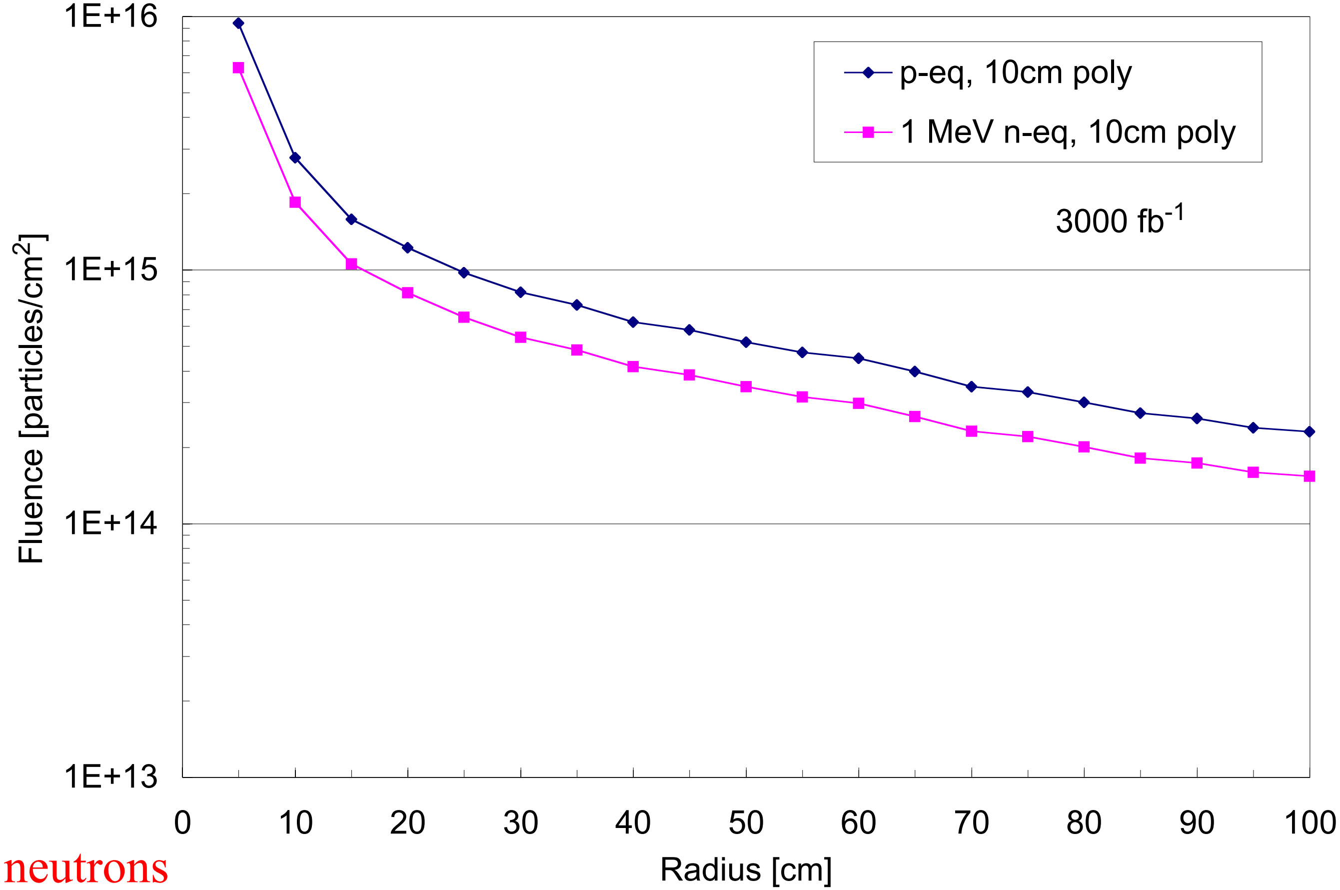






Particle Fluence

- Integrated luminosity
  - 3000 fb^{-1}
- PIXEL
  - 1×10^{16} p/cm^2
    - at 5 cm
- SCT
  - 1×10^{15} p/cm^2
    - at 25 cm
  - 3×10^{14} p/cm^2
    - at 80 cm
    - Present LHC level
- Large radii
  - Dominating particles: neutrons
    - with Poly-moderator (>5cm thick) to substitute TRT
    - >65% at R >50 cm
    - need proper account of proton and neutron damages



Radiation damage - Full Depletion Voltage

- Key word: High resistivity silicon
  - Measurements e.g., RD50
  - FDV for 300 um thick silicon
- n-bulk wafers availability
  - n-FZ(~4k) available
  - n-MCz not readily available
  - 4 kOhm･cm = ~80V
- p-bulk wafers availability
  - p-FZ(~3k) available
  - p-MCz(0.5~1k) available
  - 1 kOhm･cm = ~950V
  - FDV(p-FZ(3k))~FDV(p-MCz(1k) ?
- Relation
  - V(p)/V(n)=3*ρ(n)/ρ(p)
  - Factor 3 comes from mobility

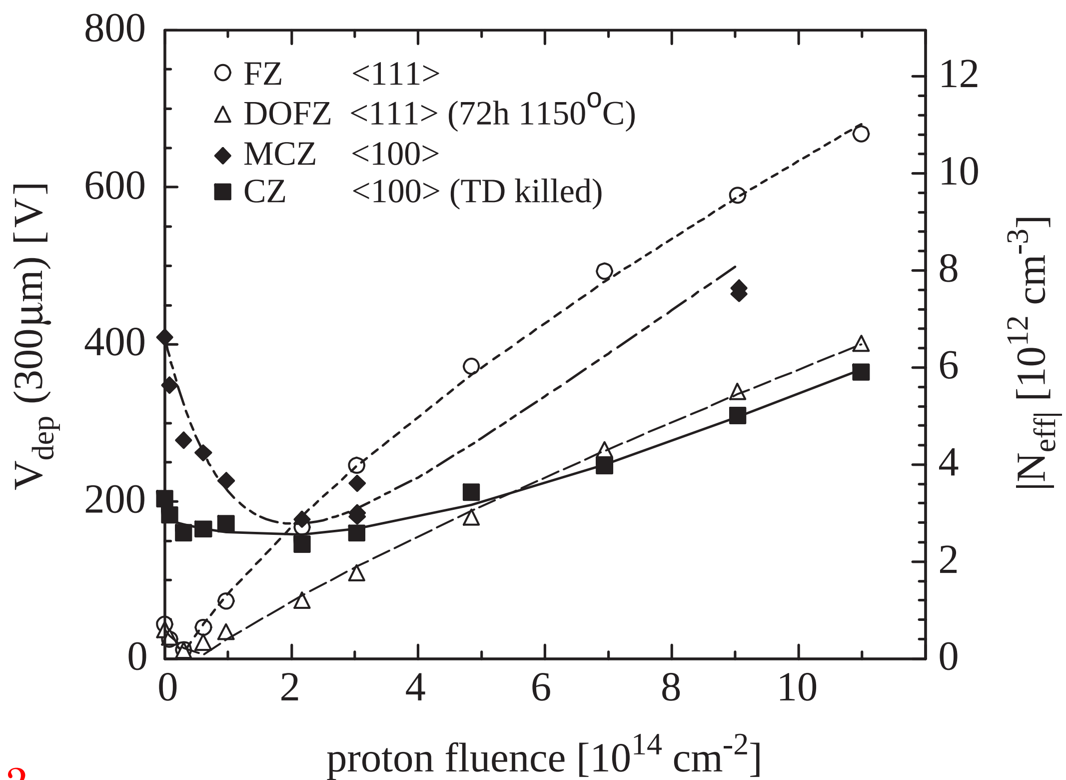
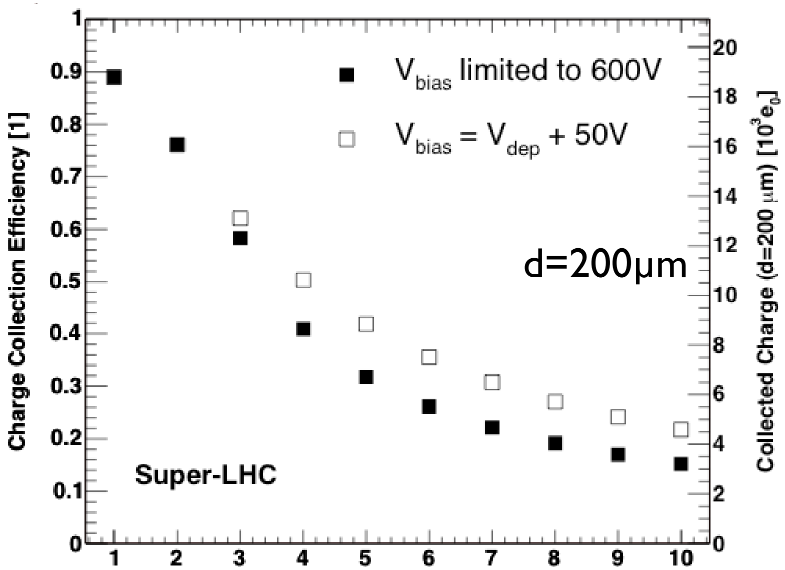


Fig. 1. Comparison of standard (FZ) and oxygenated (DOFZ) Float Zone silicon with Czochralski (CZ) and Magnetic Czochralski (MCZ) silicon detectors in a CERN irradiation scenario with 23 GeV protons [13].

Radiation damage - Charge trapping



Fluence [10^{15} n-eq/cm^2]
Olaf Krasel, Thesis Dortmund
n-bulk

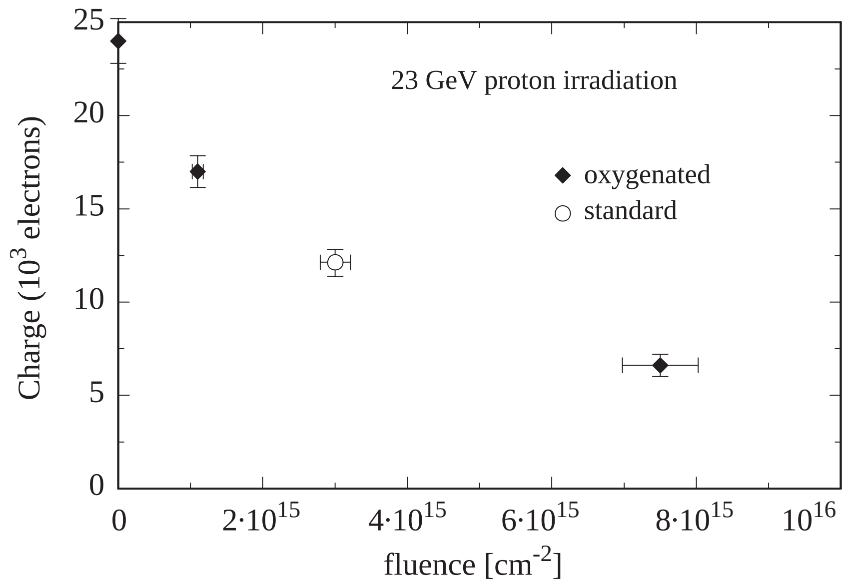


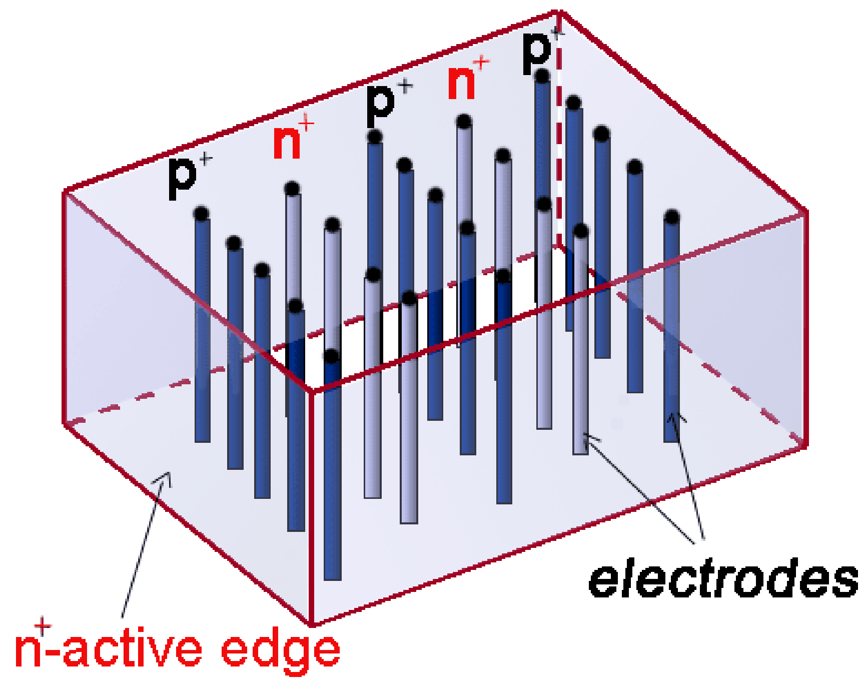
Fig. 2. Collected charge as a function of the 23 GeV proton fluence for standard and oxygenated n-in-p miniature micro-strip detectors (source: Ru^{106}, chip: SCT128A–40 MHz, 800–900 V applied to irradiated devices, measured at −20 °C) [25].

p-bulk

- $1x10^{15}$ p/cm^2
  - 70%~90% CCE, p-bulk different from n-bulk?
- $1x10^{16}$ p/cm^2
  - ~20% CCE

Silicon Sensor Development - PIXEL

- Planar electrode
  - Measurements with Deeply Oxygenated FZ n-in-n sensor (present PIXEL)
  - 1×10^{16} p/cm^2 (=~0.7×10^{16} n-eq/cm^2)
  - Operation at 600V, depletion thickness ~ 100 um
  - ~20% CCE after charge trapping
  - Collected charge ~ 3,000 e
  - Wafers
    - DOFZ, MCZ, EPI, a-Si:H
- 3D electrode, e.g.
  - n/p alternating pillars
  - 100 um distance, e.g.
  - Full thickness is sensitive, 300 um
  - Collected charge ~ 10,000 e?
- n-readout for collecting electrons
  - for faster charge collection and less ballistic deficit?

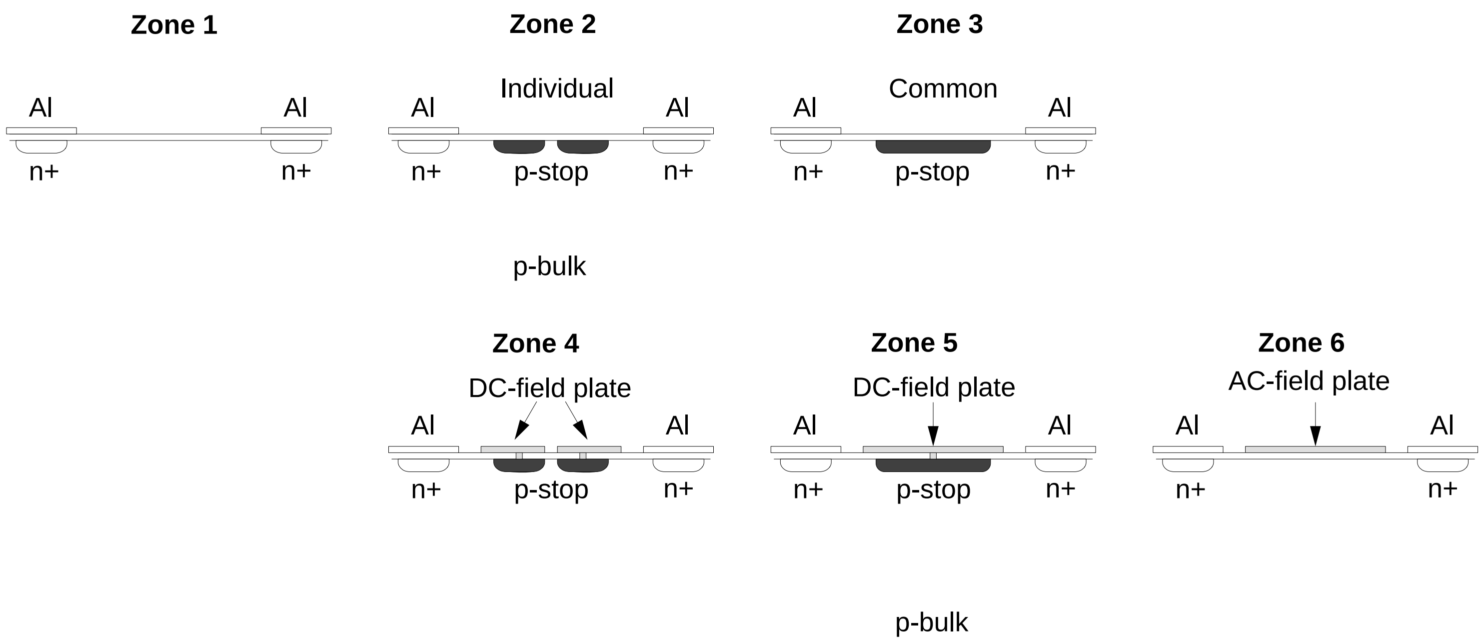


Silicon Sensor Development - SCT

- Silicon microstrip sensors
  - Region 30cm ~ 60 cm: $1x10^{15}$ p/cm^2
    - FDV 600~800V (?) for 300 um
    - Neutrons >50%
    - Prepare for partial depletion
    - n-strip: collecting electrons?
      - Faster charge collection for less ballistic deficit
    - n-strip in p-bulk (n-in-p) than n-strip in n-bulk (n-in-n) for cost reason
      - FDV: p-MCz vs. p-FZ bulk
      - n-strips isolation with p-implantation
  - Region ~80 cm: $3x10^{14}$ p/cm^2
    - Same fluence as present LHC, but neutrons dominate
    - FDV ~300V(?) for 300 um
    - n-strip vs. p-strip
      - Faster charge collection -> n-strip
      - FDV: p-MCz, p-FZ, n-FZ

Silicon Sensor Development - SCT

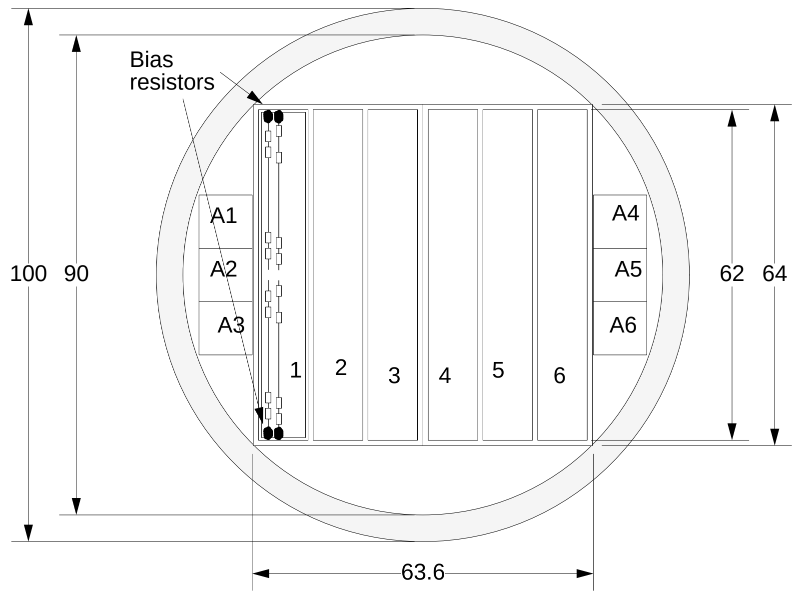
- R&D
  - p-MCz vs. p-FZ
    - with industry wafers available in quantity
    - FDV with irradiations (p and n)
    - Thermal donor effect?
  - n-strip isolation
    - p-stop (+ p-spray, + DC-field plate)



Silicon Sensor Development - SCT

- n-strip isolation study
  - in 4-inch wafer
  - 2 segments (~3cm)
  - p-stop doping level
  - being processed

Locations of miniature and test sensors TBD



Features:
Main sensor with 6 zones
2 longitudinal strips (3cm each) in a zone
80 um pitch strips in a zone
2 bonding pads per strip
1 bias ring for a zone
1 bias resistor per strip at end as shown
6 10mm x 10mm miniature sensors (A)

Zones:
1: No p-stop
2: Individual p-stop
3: Common p-stop
4: Individual p-stop with extended DC field-plate
5: Common p-stop with extended DC field-plate
6: Common AC field-plate with external potential pad

Summary

- SLHC upgrade is foreseen in ~2015
  - IR Q-magnet radiation damage
- Luminosity upgrade
  - $\sim 10^{35}$ $cm^{-2}s^{-1}$ by x1.7 protons/bunch, x1/2 bunch length, x2 bunches
- ATLAS upgrade
  - Inner tracker to be replaced for all silicon
- Silicon sensor developments
  - PIXEL
    - 1×10^{16} p/cm^2
    - Planar (DOFZ, MCZ, EPI, a-Si:H) or 3D electrodes
  - SCT (silicon microstrip sensors)
    - 1×10^{15} and 3×10^{14} p/cm^2
    - Design optimization in multi-parameter space
      - Occupancy, Pitch, No. of strips, Width, Length, Radius, Physics performance, …
    - R&D for partial depletion and less ballistic deficit
      - p-MCZ vs. p-FZ
      - n-strip isolation

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