Charge Collection Efficiency for Planar Silicon Detectors after Doses up to 10^{15} n_{eq} cm^{-2}

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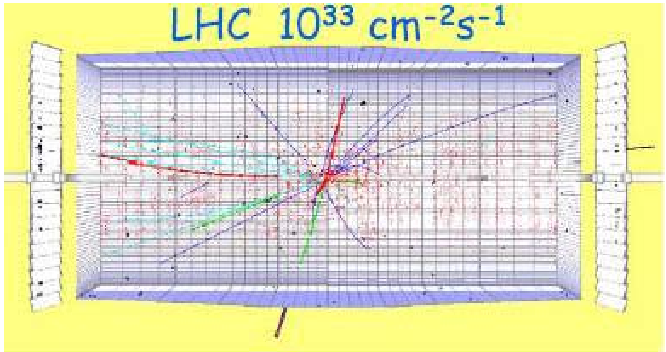
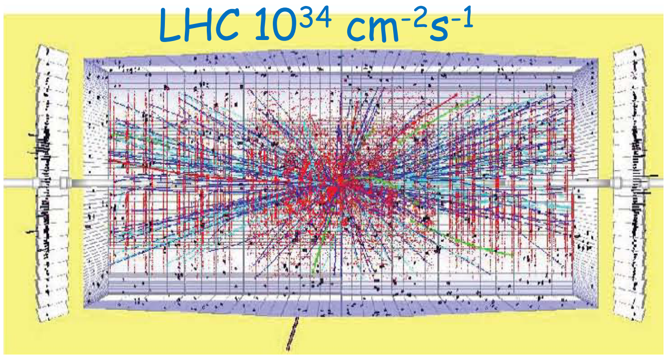
The SLHC Upgrade

- Super-LHC is a factor of 10× luminosity upgrade to the Large Hadron Collider (LHC)



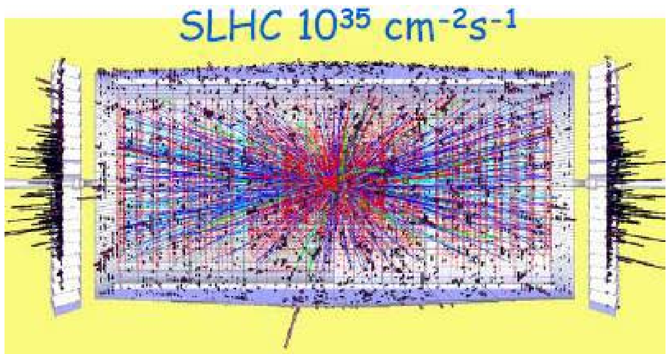
LHC (2008-2015?),
~1 billion collisions per sec
$\mathcal{L} = 10^{34}$cm^{-2}s^{-1} , 10years, 500 fb^{-1}



Super-LHC (2015?-),
~10 billion collisions per sec
$\mathcal{L} = 10^{35}$cm^{-2}s^{-1} , 5 years, 2500 fb^{-1}

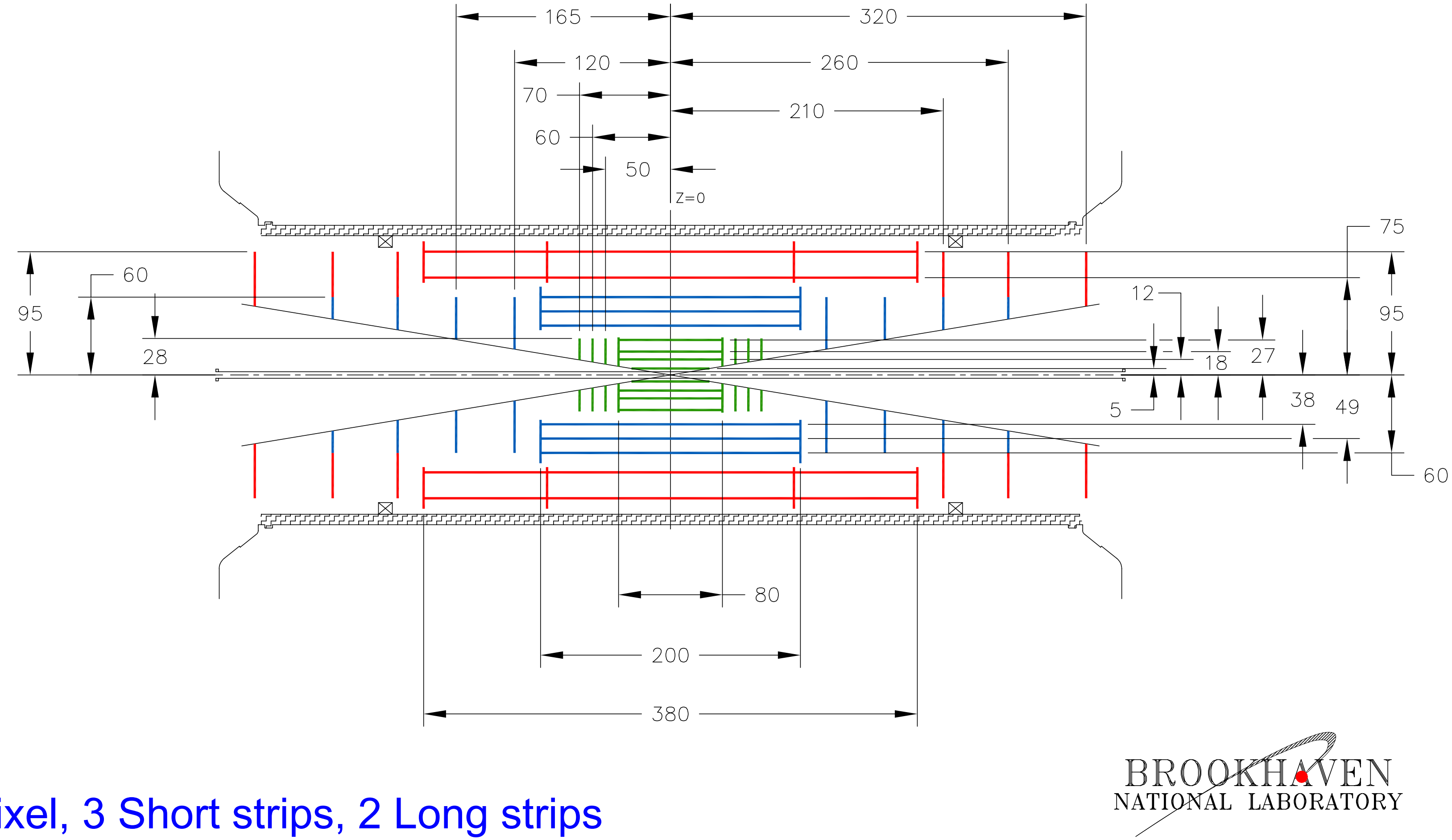
The main challenges to the vertexing and tracking detectors are:

- Charge collection after high radiation doses
- Density of charged particles (Segmentation)
- Thermal management (Runaway)



This talk focuses on charge collection issues for silicon microstrip detectors

ATLAS Upgrade Layout

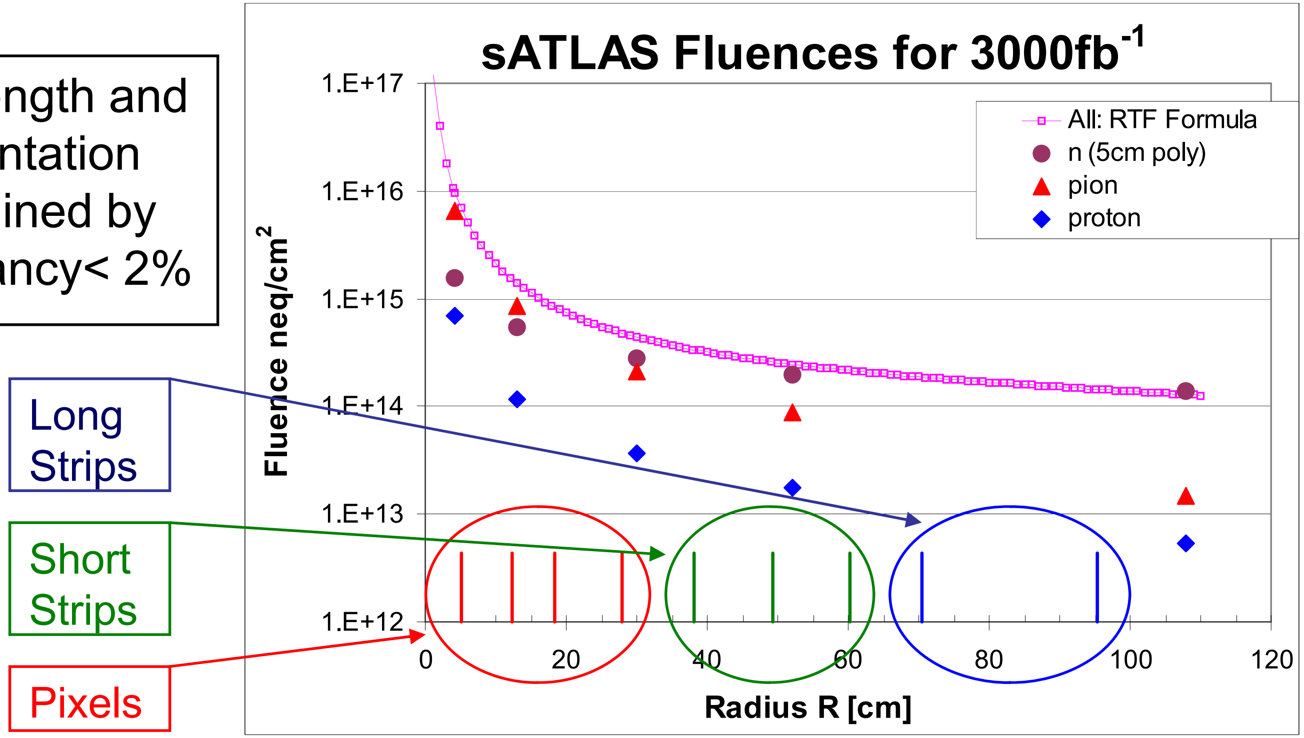


4 Pixel, 3 Short strips, 2 Long strips

<u>100 m² of long strips, 60 m² short strips</u>, at least 5 m^2 of pixels

Fluence in Proposed sATLAS Tracker

Strip length and segmentation determined by occupancy< 2%



ATLAS Radiation Taskforce http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/RADIATION/RadiationTF_document.html

Mix of neutrons, protons, pions depending on radius R

Long and short strips damage largely due to neutrons

Pixels damage due to neutrons and pions

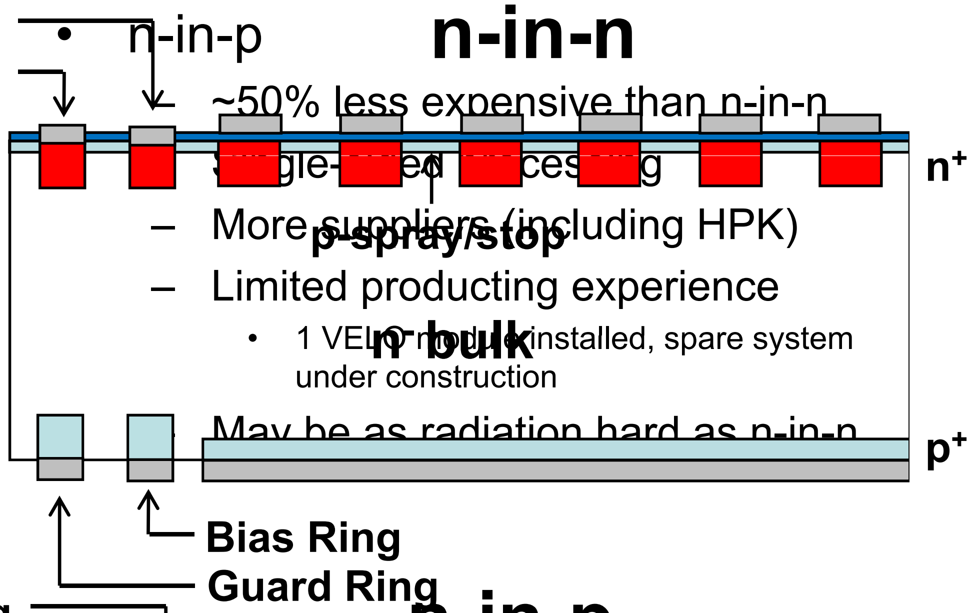
Design fluences for sensors (includes 2x safety factor) **:**

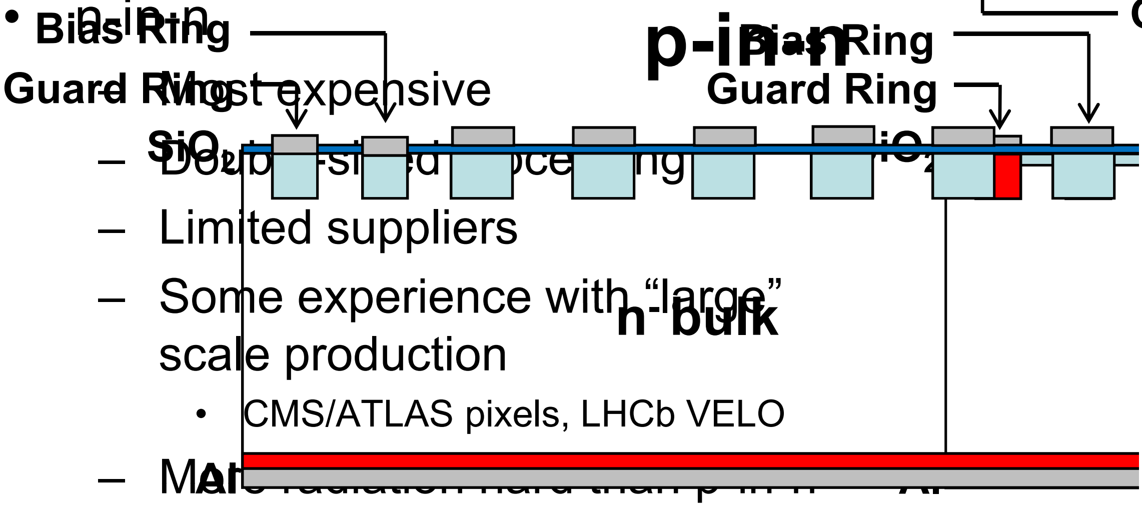
Innermost Pixel Layer:	1-1.6*10^{16} n_{eq}/cm^2 = 500 Mrad
Outer Pixel Layers:	3*10^{15} n_{eq}/cm^2 = 150 Mrad
Short strips:	**1*10^{15} n_{eq}/cm^2 = 50 Mrad**
Long strips:	**4*10^{14} n_{eq}/cm^2 = 20 Mrad**

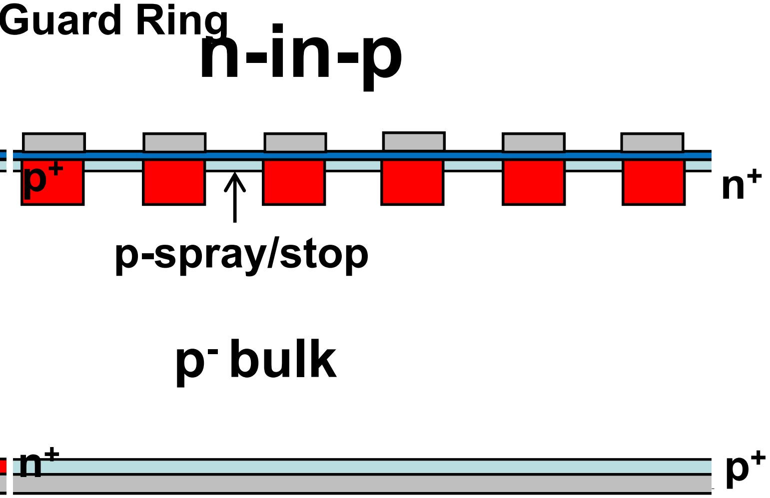
Need to study response to both neutral (neutrons) and charged (proton) particle irradiations

Geometry Choices

- p-in-n
  - Least expensive
  - Single-sided processing
  - Available from all foundries
  - Most experience in production
    - All strips at CMS/ATLAS/ALICE, Tevatron, b-factories, …
- n-in-p
  - ~50% less expensive than n-in-n
  - Single-sided processing
  - More suppliers (including HPK)
  - Limited producting experience
    - 1 VELO module installed, spare system under construction
  - May be as radiation hard as n-in-n
- n-in-n
  - Most expensive
  - Double-sided processing
  - Limited suppliers
  - Some experience with "large" scale production
    - CMS/ATLAS pixels, LHCb VELO
  - More radiation hard than p-in-n







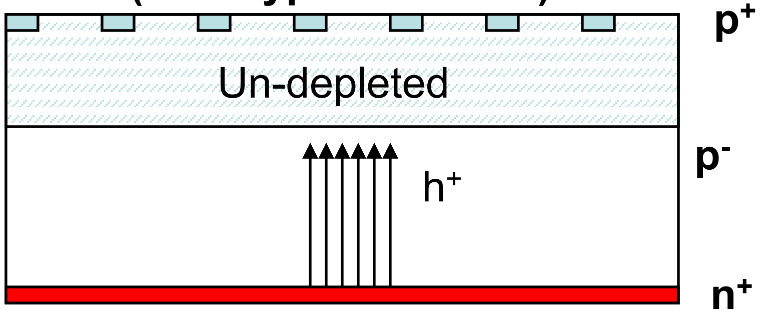
P-strip vs. N-strip Readout

Effect of trapping on the Charge Collection Efficiency (CCE)

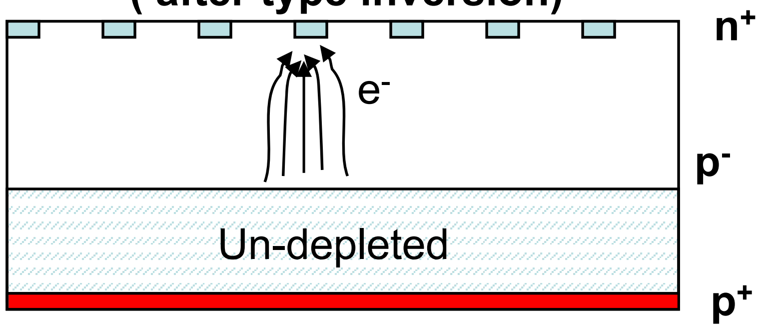
$$Q_{tc} \cong Q_0 \exp(-t_c/\tau_{tr}),\ 1/\tau_{tr} = \beta\Phi.$$

t_C is collection "time", τ_{tr} is effective trapping time

"Standard" p-in-n geometry (after type inversion)



"New" n-in-p geometry
"New" n-in-n geometry
(after type inversion)

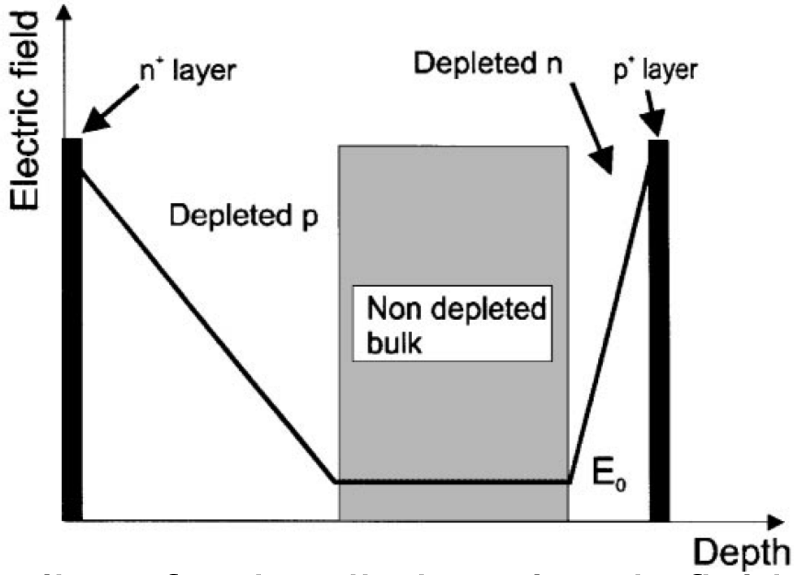


Type inversion turns lightly doped material to "p" type

- 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

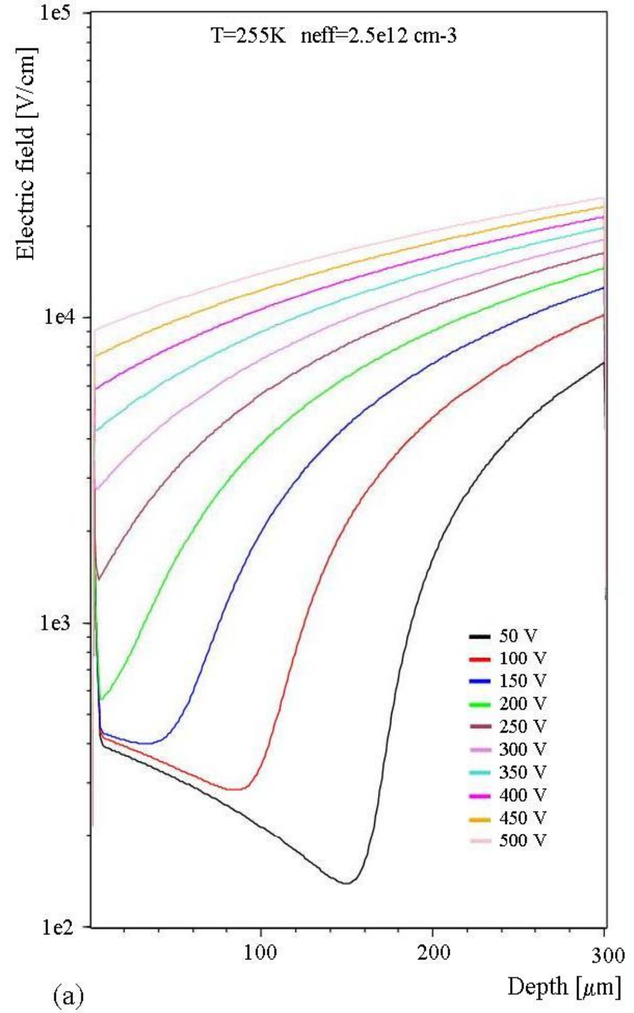
Double Junction



In reality, after irradiation electric fields show a double junction structure with a non-depleted bulk in the middle of the sensor below the full depletion voltage

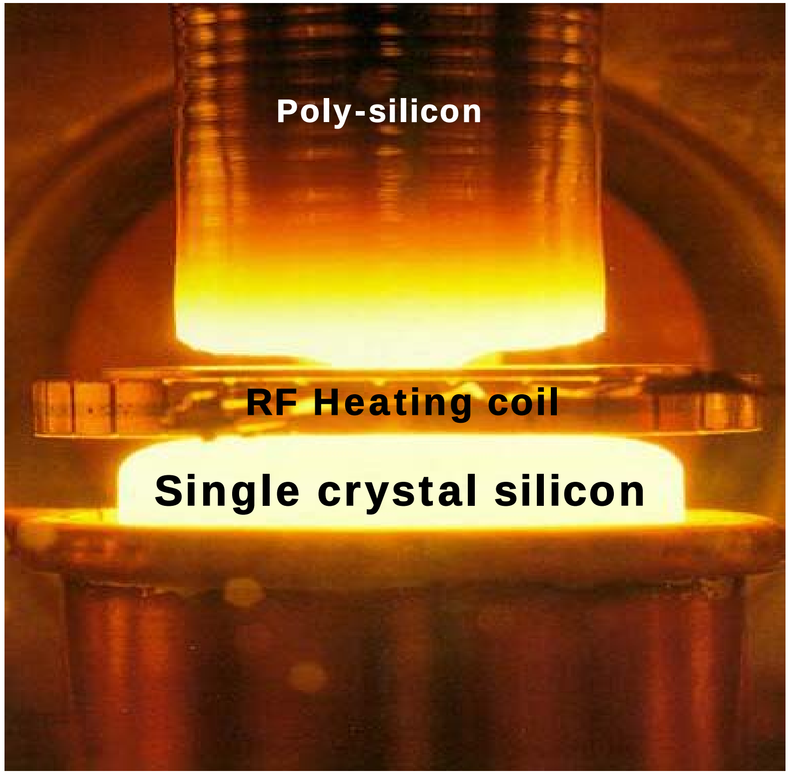
See G. Casse, et. al., NIMA **426** (1999) 140-146 and G. Kramberger, et. al., NIMA **579** (2007) 762-765 for details

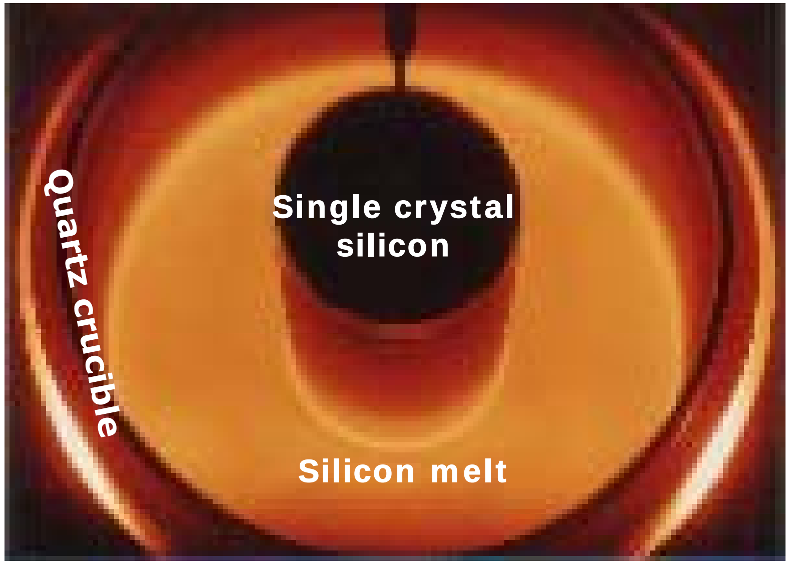
P-side **N-side**



ISE-TCAD simulation after 6×10^{14} p cm^{-2}

Wafer Technology Choices





- Float Zone (FZ)
  - Most experience
  - Relatively low initial V_{FD} (20-150V)

- Magnetic Czochralski(MCz)
  - More oxygen
    - More rad. hard??
  - Less uniformity in resistivity within wafer??
  - Less expensive??
  - Higher initial V_{FD} (150-700 V)

Miniature Silicon Micro-strip Sensors

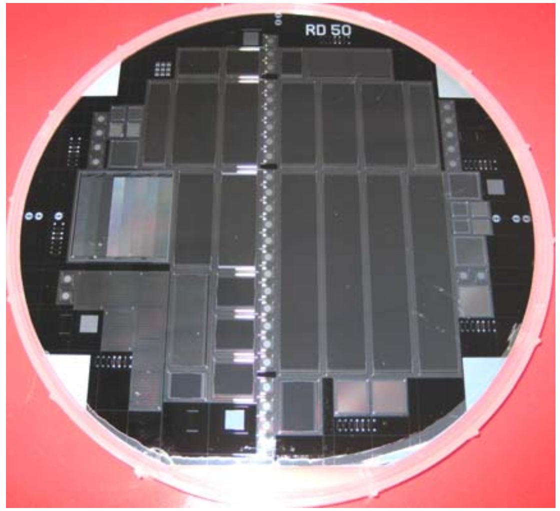
Micron/RD50 (6” wafers)

RD50 mask (see: http://rd50.web.cern.ch/rd50/)

Microstrip, ~1x1 cm^2, 128 strips, 80 μm pitch, ≤300μm thickness

- n-in-p FZ (V_{FD} ~100 V)
- n-in-p MCz(V_{FD}~550 V)
- n-in-n FZ (V_{FD} ~70V)
- n-in-n MCz (V_{FD}~170 V)
- p-in-n FZ (V_{FD}~70 V)
- p-in-n MCz (V_{FD} ~170 V)

6 in.



Irradiation and dosimetry (Neutrons):
Jozef Stefan Institute, Ljubljana, Slovenia: **V. Cindro, et. al.**

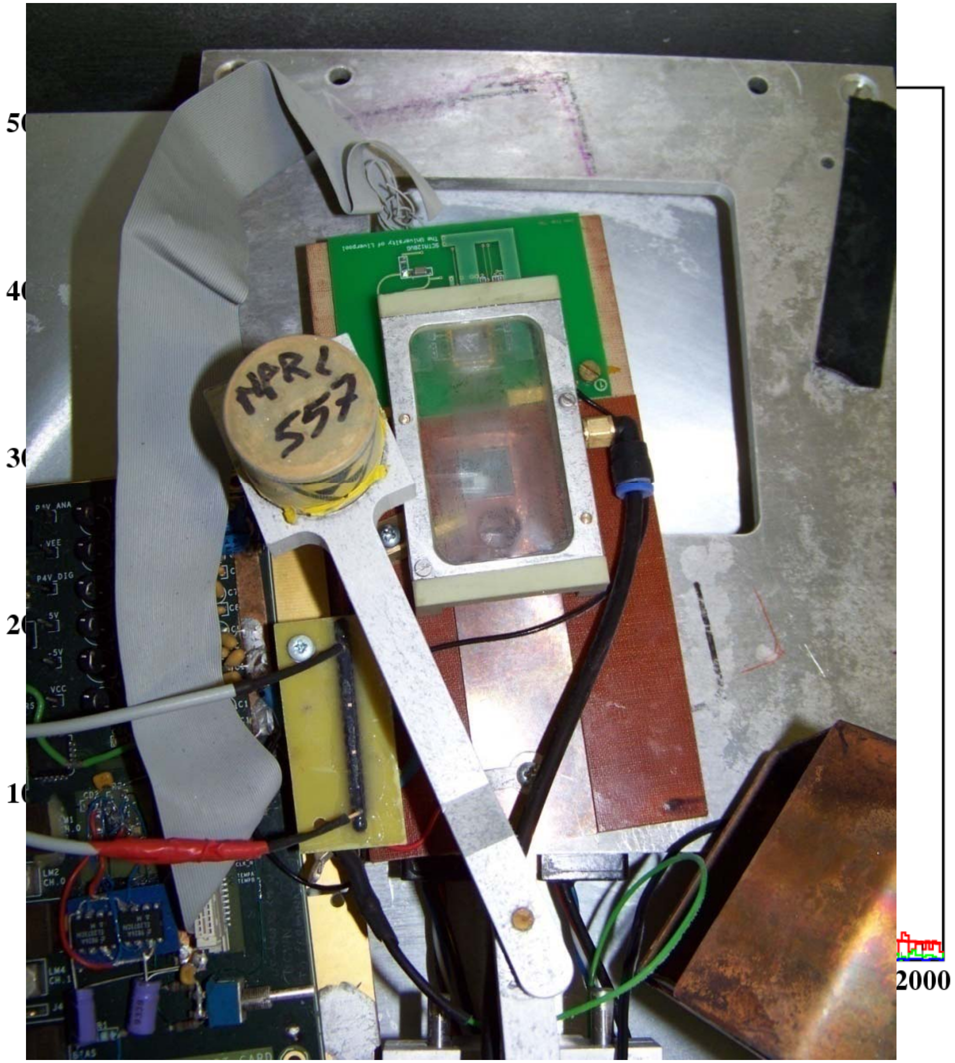
Irradiation and dosimetry (24 GeV Protons):
CERN PS Irrad1 facility: **M. Glaser, et. al**.

Irradiation and dosimetry (26 MeV Protons):
Karlsruhe: **W. de Boer, et. al.**

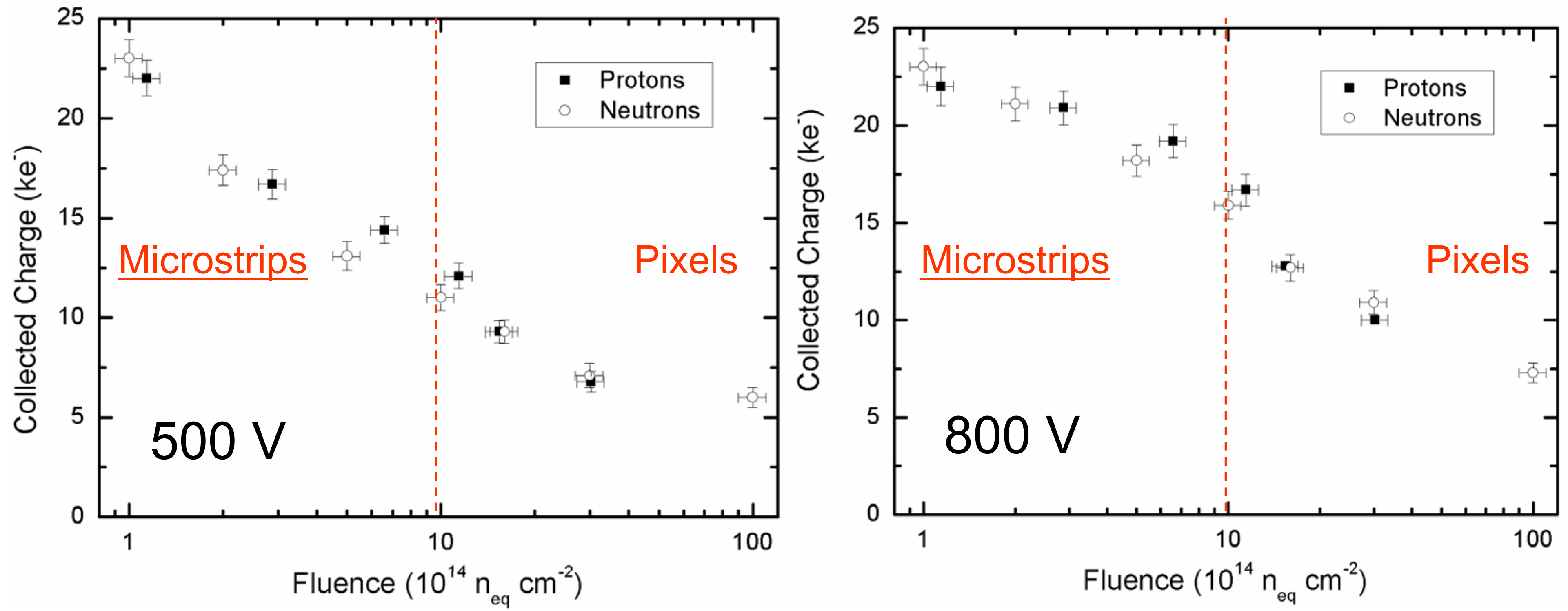
Most of this work has been performed using material and detectors produced within the framework of RD50.

Experimental Setup

- Charge collection efficiency (CCE) measured using detachable read-out analogue electronics chip (SCT128) clocked at LHC speed (40MHz clock, 25ns shaping time).
  - Measurements performed at a temperature down to -25 °C with N_2 flush
- ^{90}Sr fast electron source triggered with scintillators in coincidence used to generate signal.
- The system is calibrated to the most probable value of the MIP energy loss in a non-irradiated 300µm thick detector (~23000 e^-).



Liverpool Charge Collection Studies

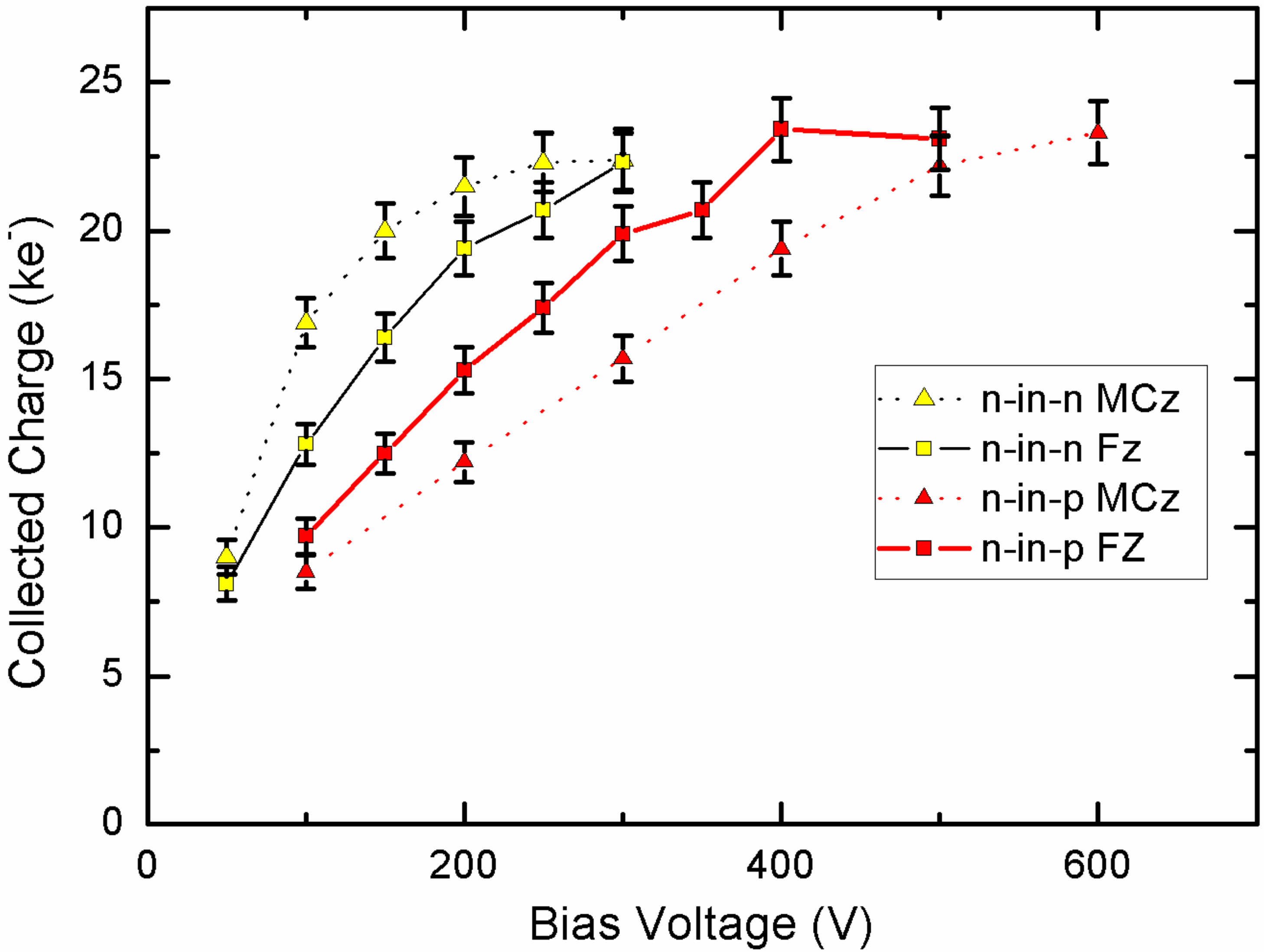


n-in-p FZ planar technology candidate for all layers

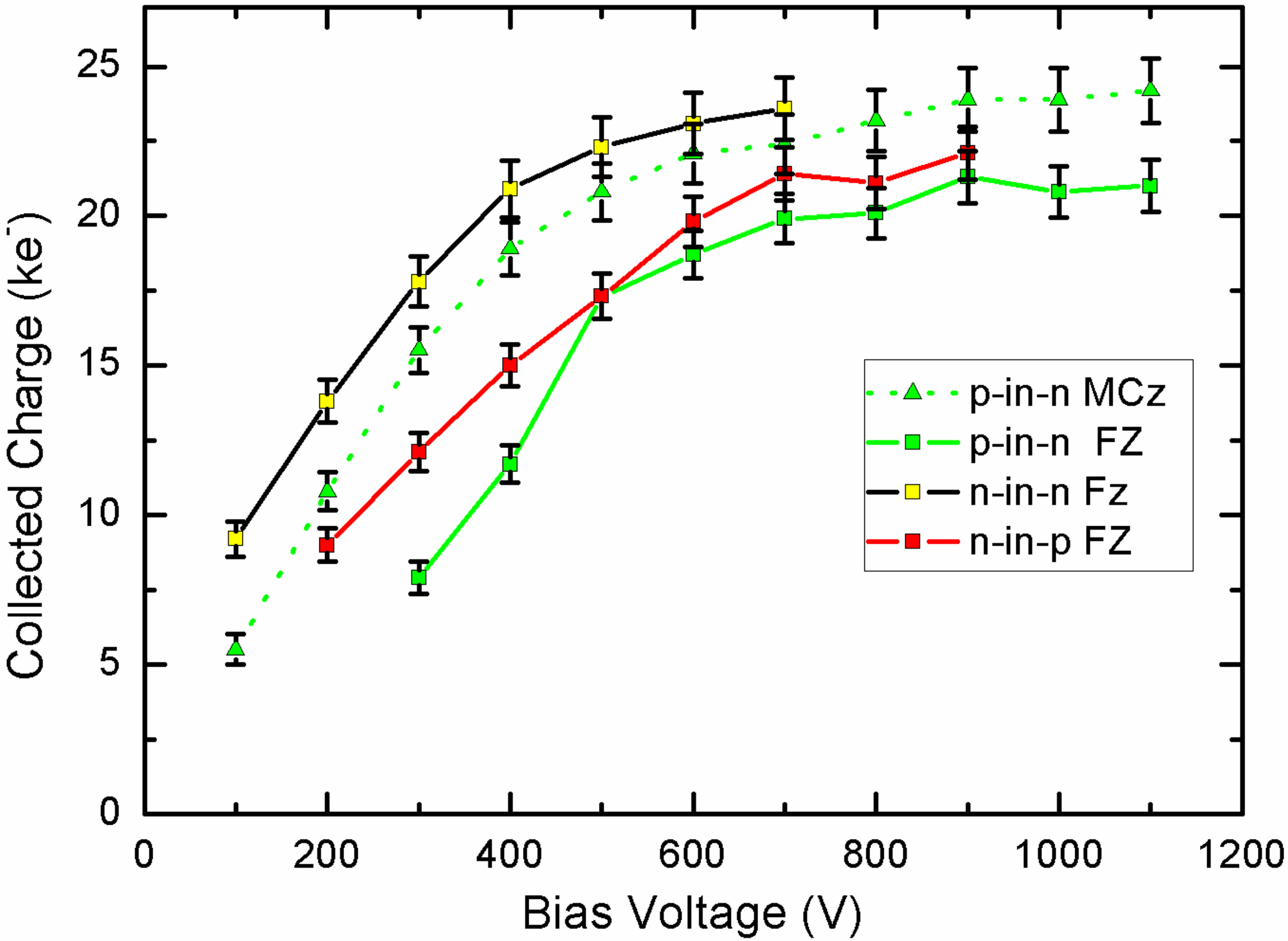
Higher doses (>1×10^{16} n_{eq} cm^{-2}) to be reported soon

n-in-p, n-in-n, p-in-n FZ & MCz comparisons for <u>microstrip doses</u> to follow:

1×10^{14} n cm^{-2}

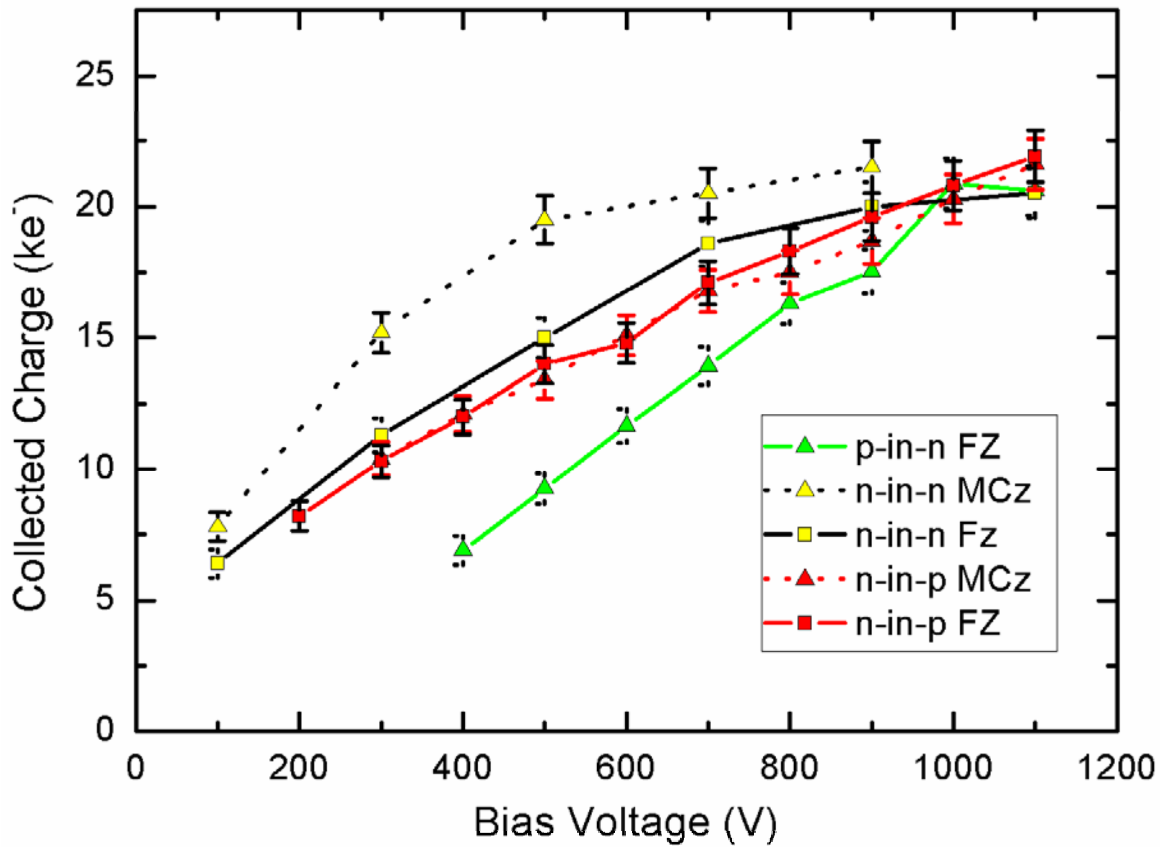


2×10^{14} n cm^{-2}



5×10^{14} n cm^{-2}

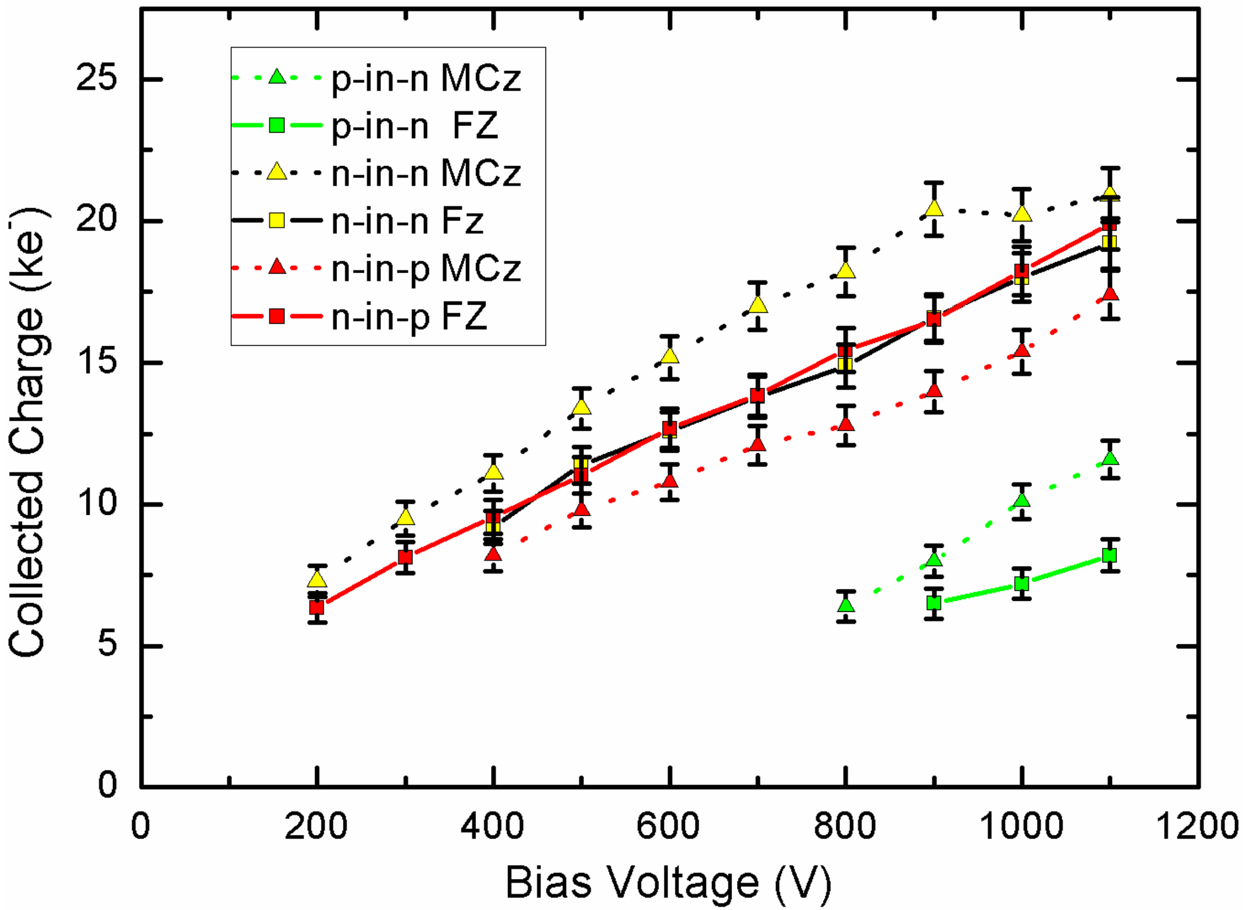
- Design flux for long (9 cm) strips
  - R=70-100 cm
    - Includes 2× safety factor
- p-in-n FZ extremely marginal CCE@500 V
- n-in-n and n-in-p show sufficient CCE@500 V for efficiency tracking (S:N >10:1)
  - Expected noise: ~1300 enc
  - Can be reduced to ~950 enc with 20% increase in chip power



Only n-in-n MCz significantly better

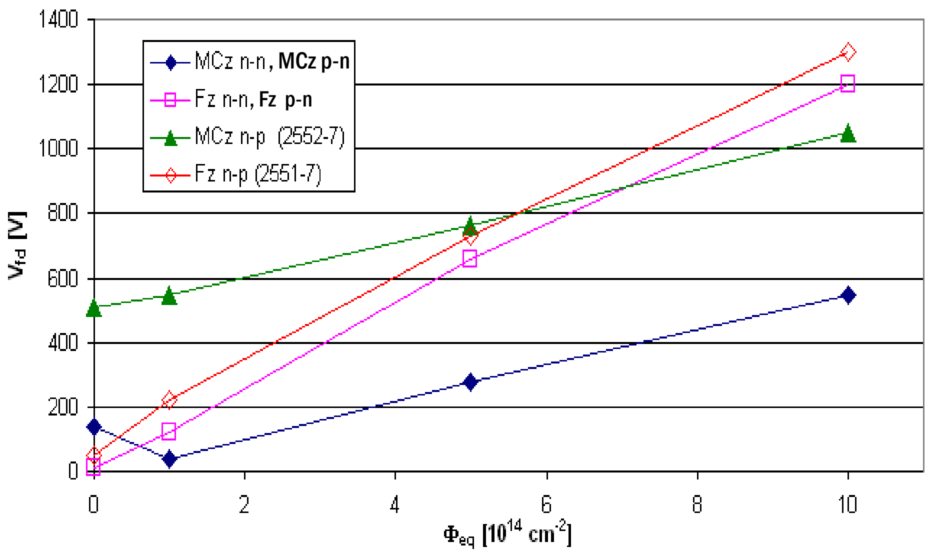
1×10^{15} n cm^{-2}

- Design flux for short (2.5 cm) strips
  - R=40-60 cm
    - Includes 2× safety factor
- n-in-n and n-in-p show sufficient CCE at 500 V for efficiency tracking (S:N >10:1)
  - Expected noise: 750 enc

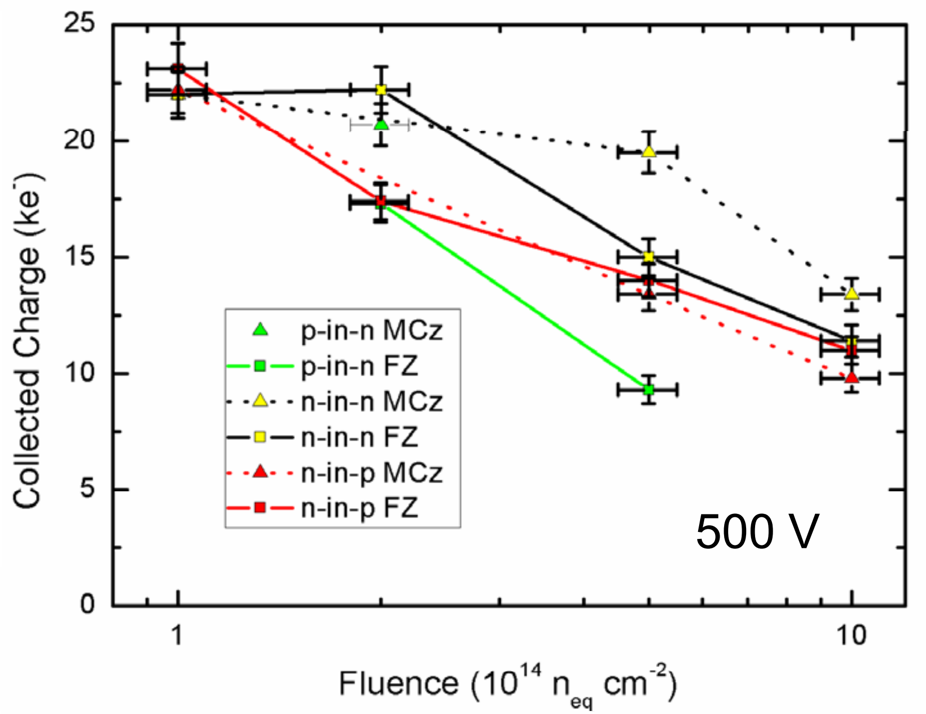


Only n-in-n MCz significantly better

Neutron Summary

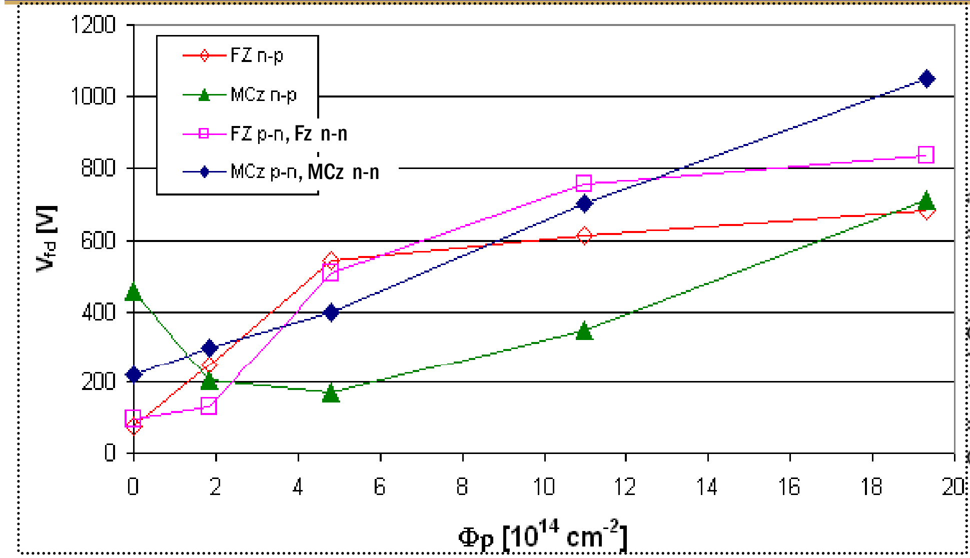


G. Kramberger, "Charge collection measurements on MICRON RD50 detectors", ATLAS Tracker Upgrade Workshop, Valencia 11-14 December 2007, http://ific.uv.es/slhc/ATLASUpgrade/

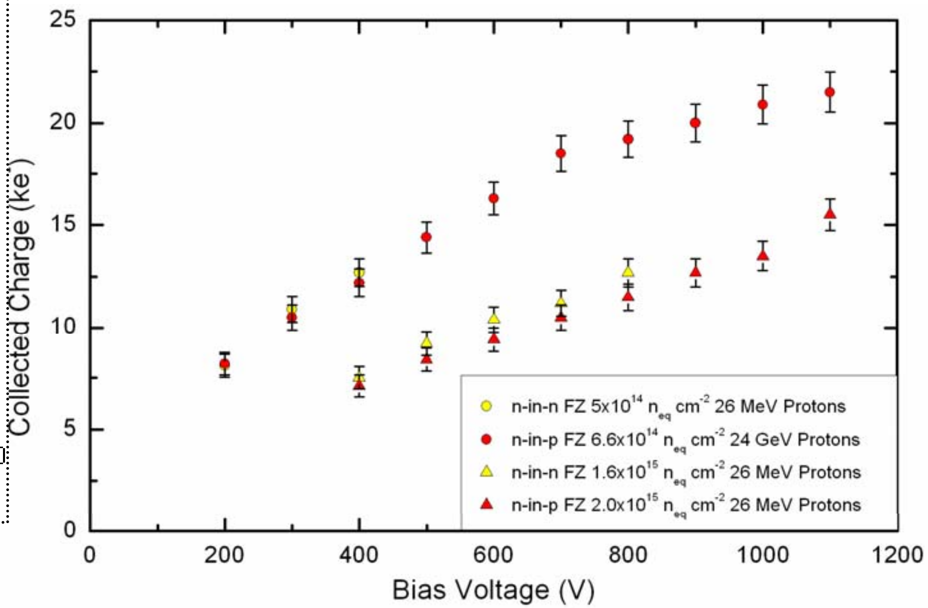


- Both p-in-n FZ and p-in-n MCz sensors show insufficient charge collection for short strip regions (>5×10^{14} n_{eq} cm^{-2})
- n-in-n FZ, n-in-p FZ, and n-in-p MCz similar in terms of CCE at these doses
  - n-in-n FZ slightly better at doses < 5×10^{14} n_{eq} cm^{-2}
- n-in-n MCz shows best performance as expected from CV measurements

Proton Irradiations

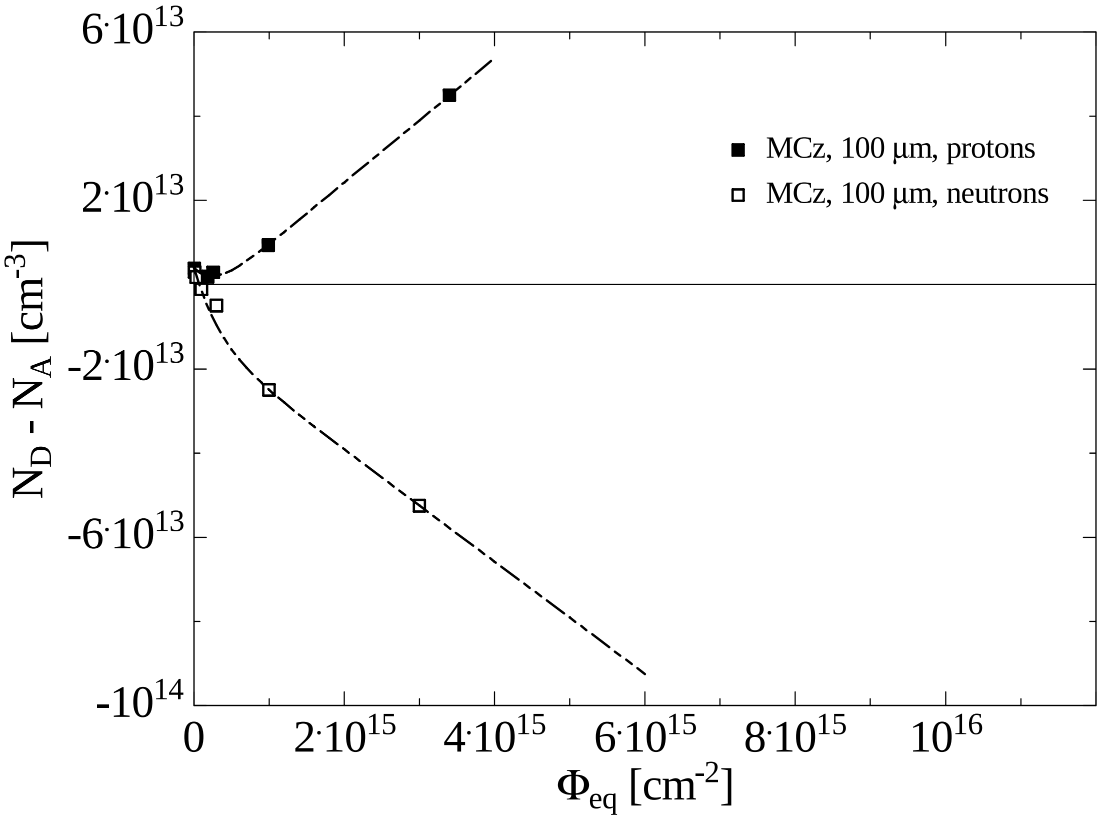


G. Kramberger, et.al., 3rd Workshop on Advanced Silicon Radiation Detectors (3D and P-type Technologies), Barcelona 14-16 April 2008, http://indico.cern.ch/conferenceDisplay.py?confId=28165



- At the proposed inner radii of the short strips, charged particles are ~50% of flux
  - V_{FD} measurement with proton irradiation shows significant differences from neutron irradiations
- **CCE measurements after pion and more for proton irradiation needed**
- As of now, we only have n-in-n FZ and n-in-p FZ results available
  - Both show similar CCE
- More n-in-p MCz and n-in-n MCz wafer currently in process
  - New results available in 2009

Mixed Irradiations (MCz)



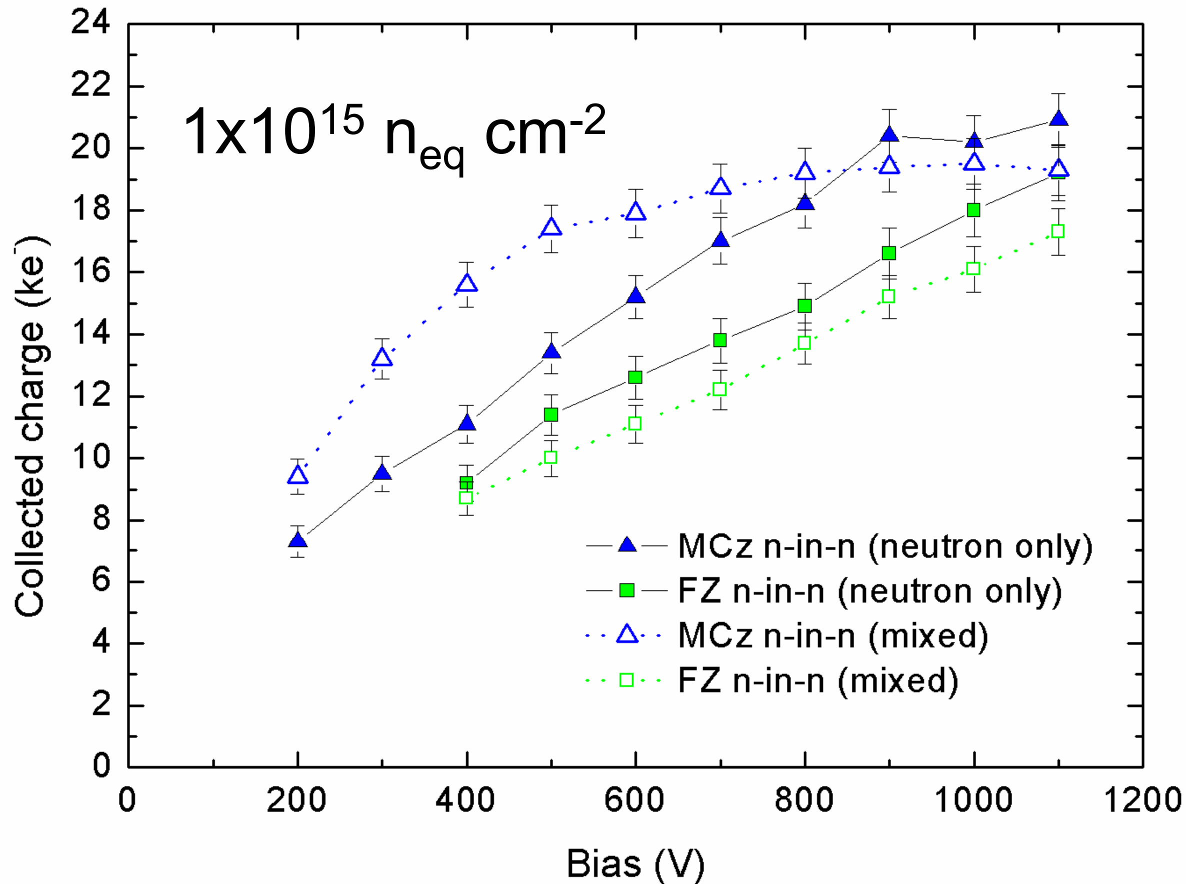
E. Fretwurst et al., 11th RD50 workshop

Practical outcome: possible partial compensation of N_{eff}, therefore **better CCE at low voltages**?

- $\beta > 0$ **(dominant donor creation) for protons (more point defects than clusters)**
- $\beta < 0$ **(dominant acceptor creation) for neutrons (more clusters than point defects)**

Mixed Irradiations (Neutrons+Protons)

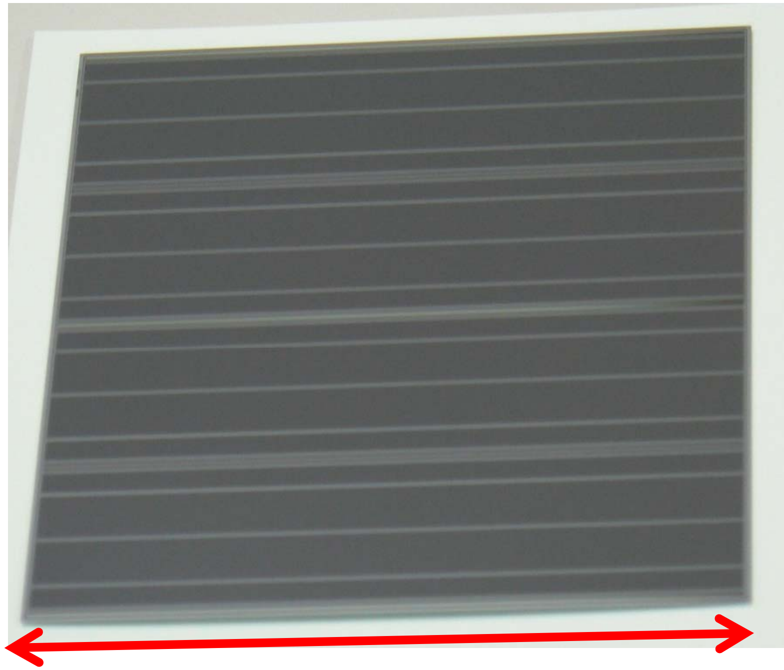
- Both FZ and MCz show "predicted" behaviour with mixed irradiation
  - FZ doses add
    - $|N_{eff}|$ increases
  - MCz doses compensate
    - $|N_{eff}|$ decreases



Needs further study with both nMCz and pMCz substrates and differing mixed doses

Conclusions

- The SLHC upgrade is planned for 2015
  - Current p-in-n technology used unable to cope with expected fluences
- Both n-in-p and n-in-n geometries in both FZ/MCz materials have sufficient radiation hardness
  - **n-in-n MCZ had best results**
- FZ n-in-p (single-sided) chosen technology for short and long strip regions for ATLAS upgrade
  - Cost and availability of high production capacity: Hamamatsu (HPK)
  - Full-size HPK prototypes already in hand



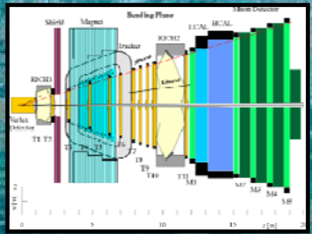
10 cm × 10 cm

- All geometries should be studied further for smaller, highly irradiated, inner regions

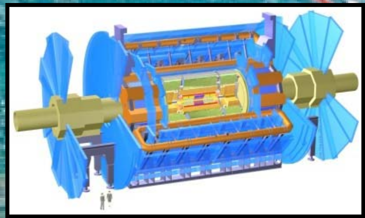
CERN Large Hadron Collider

- Proton on proton collisions: $\sqrt{s}$ = 14 TeV
  - ***Highest Energy Collider Ever***
  - 25 ns between beam crossings
  - Peak Luminosity 10^{34} cm^{-2} s^{-1}
  - 20 minimum bias collisions per beam crossing
- **First Beams September 2008!!!**

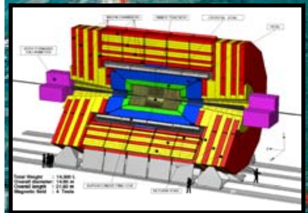
LHCb



ATLAS



CMS



Alice