Research towards a possible upgrade of the LHCb VErtex LOcator

Overview

- The LHCb detector and the VELO
- VELO sensor performance
- Possible upgrade solution
  - Czochralski Silicon
- Current status

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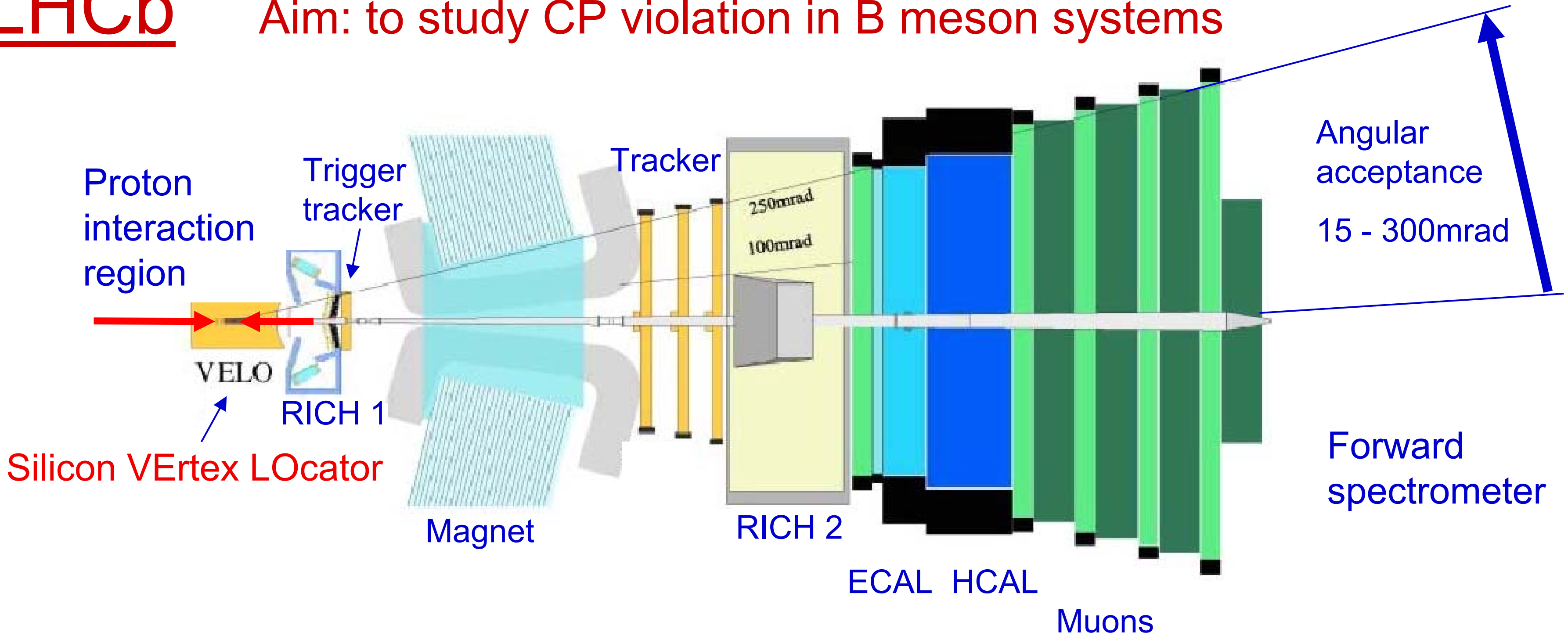
IoP HEPP Conference, University College Dublin
21st-23rd March 2005

LHCb

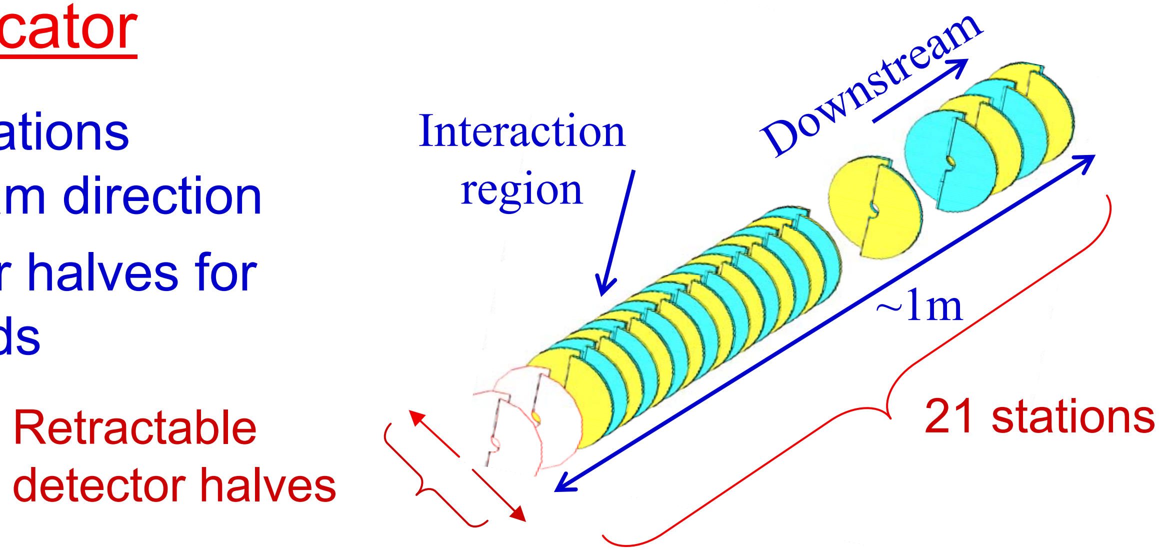
Aim: to study CP violation in B meson systems



LHCb VErtex Locator

- 21 silicon tracking stations placed along the beam direction
- 2 retractable detector halves for beam injection periods

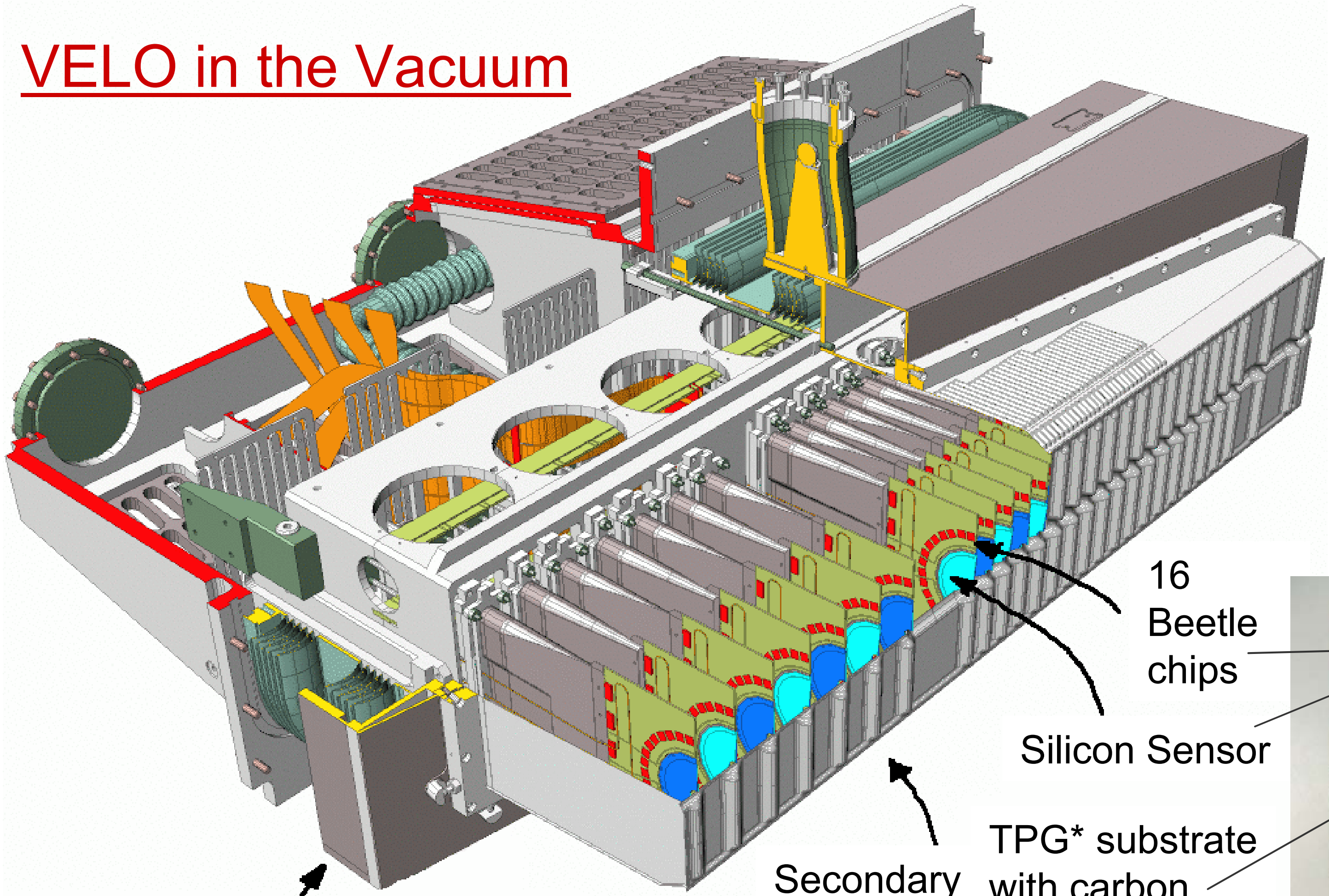
  (up to 30 mm)

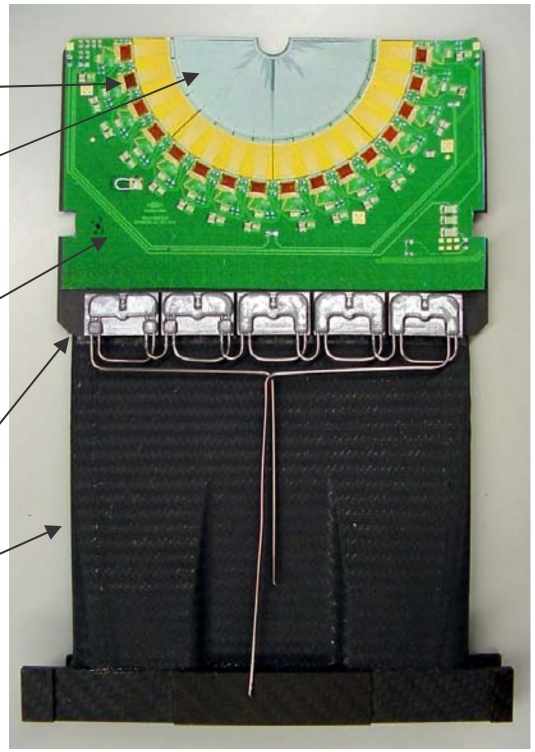


VELO in the Vacuum

Double sided modules

(1 x R and 1 x Φ sensor)





Silicon operating temperature -7°C

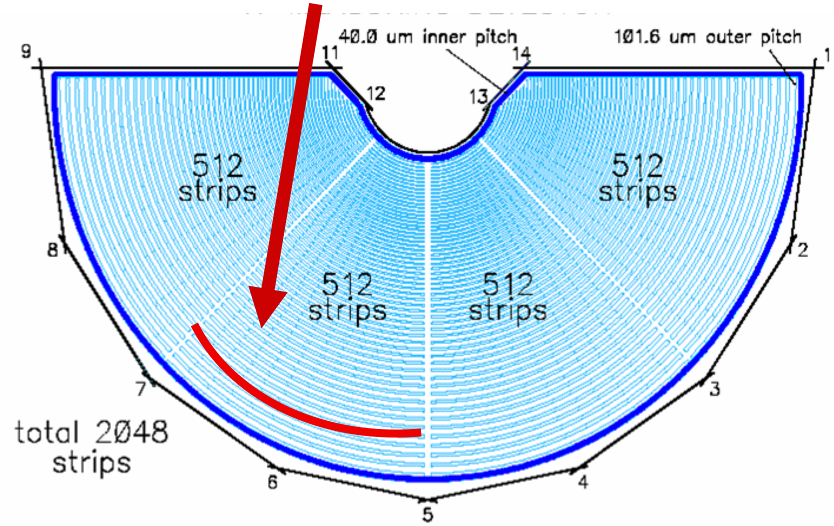
*Thermalised Pyrolytic Graphite

VELO Sensor design

- 2 sensor types: R and Φ
  - R measuring gives radial position
  - Φ measuring gives an approximate azimuthal angle
- Varying strip pitch
  - 40 to 102 μm (R – sensor)
  - 36 to 97 μm (Φ – sensor)
- First active silicon strip is 8.2 mm from the beam line
- n^+-on-n DOFZ silicon
  - minimises resolution and signal loss after type inversion
- Double metal layer for detector readout

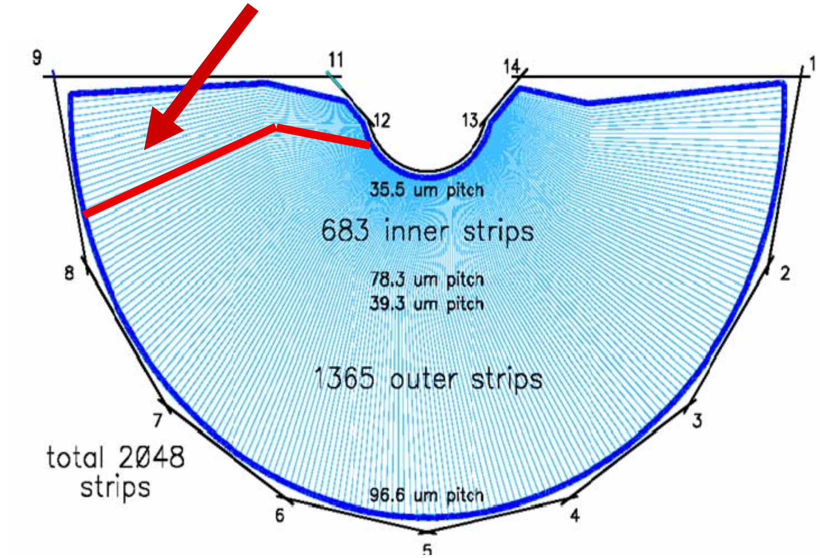
R-measuring sensor:

(concentric strips)

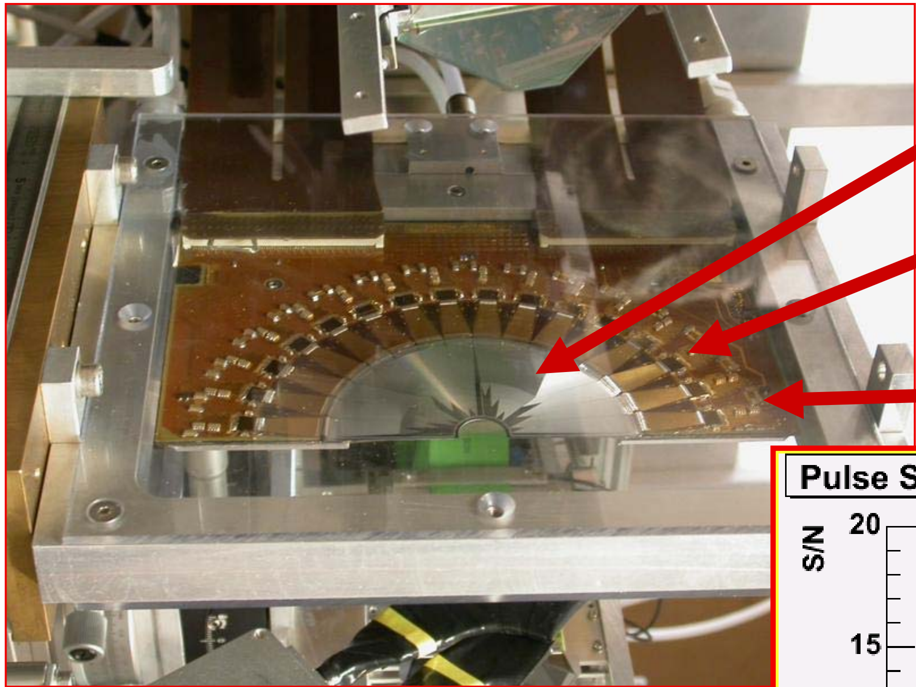


Φ–measuring sensor:

(Radial strips with a stereo angle)



2004 test beam results



300μm n⁺-on-n R sensor

16 readout chips

(Beetle 1.3)

Prototype hybrid (K03)

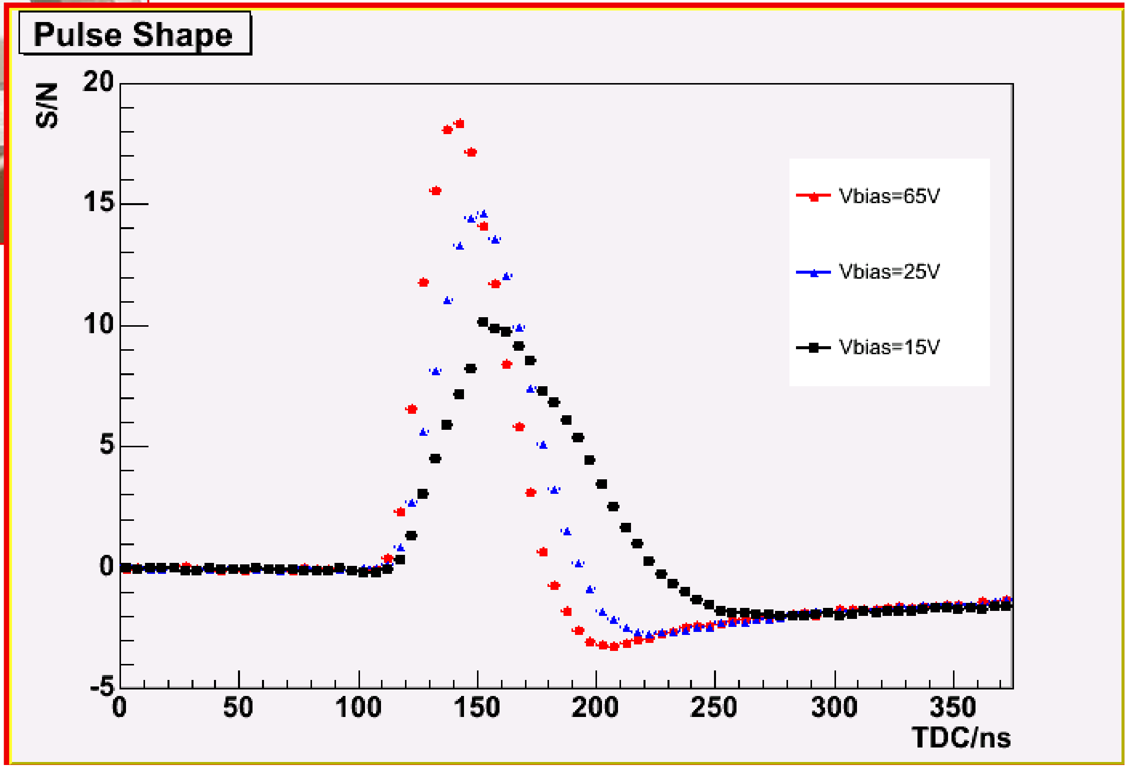
300μm S:N =19:1

200μm S:N =13.5:1

spillover: signal at 25ns after peak in % of the peak signal

< 30% (100V bias)

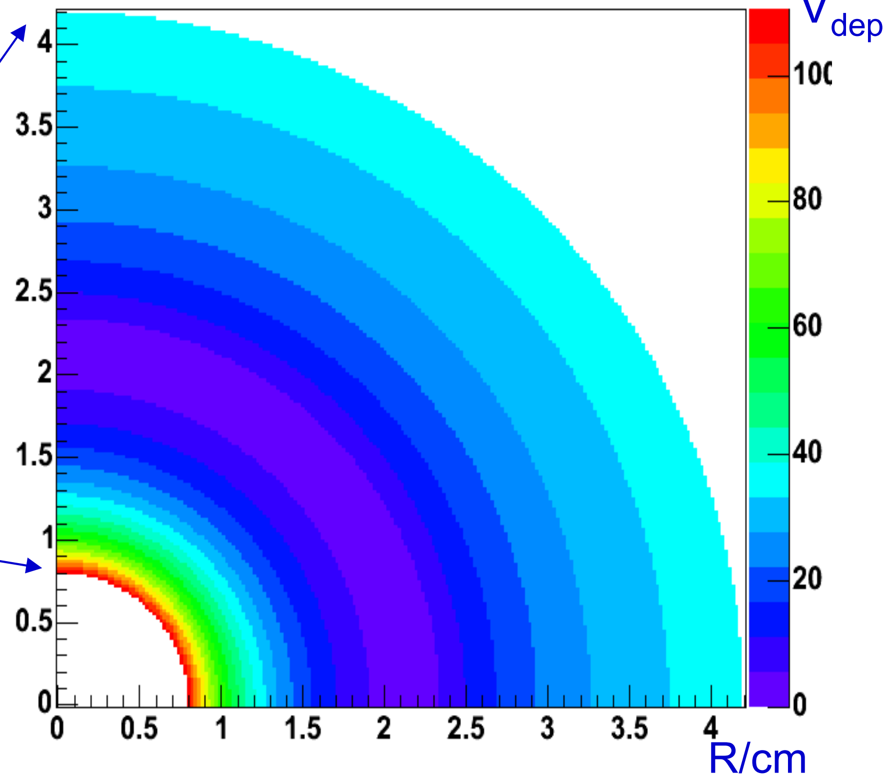
(30% is the maximum before displaced vertex trigger performance degraded.)



VELO environment

- VELO sensors operate in a harsh non-uniform radiation environment
  - fluence to outer regions $5 \times 10^{12}\ n_{eq.}/cm^2$
  - fluence to inner regions $1.3 \times 10^{14}\ n_{eq.}/cm^2$
- Estimated to survive 3 years (~2010)
  - A replacement/upgrade is foreseen

Illustration of the depletion voltage across the silicon sensor



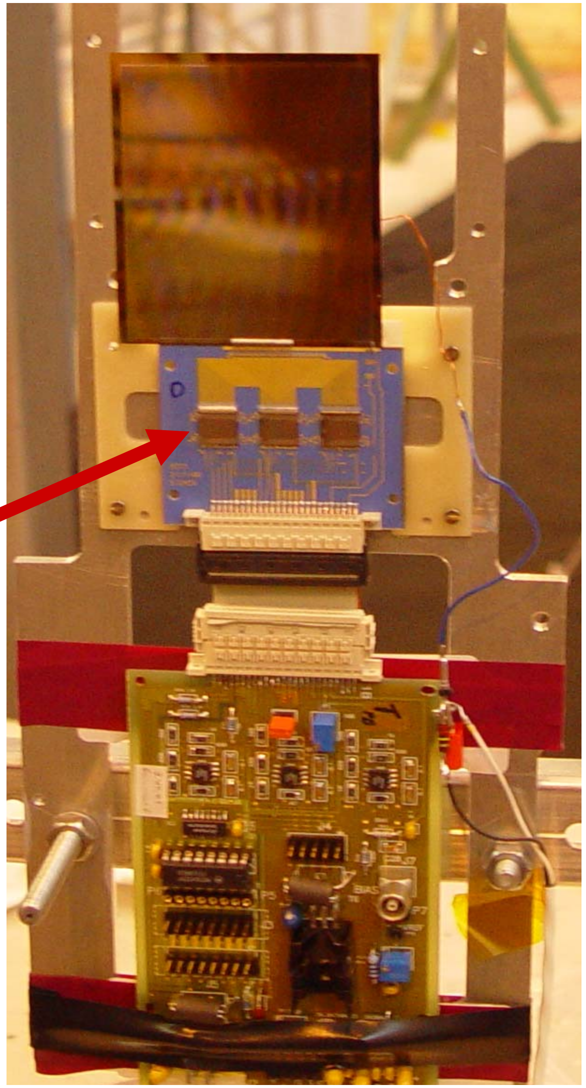
If the sensors move closer to the beam OR we increase the luminosity then a more radiation hard silicon solution is required.

Possible upgrade choices for the silicon

n$^+$-on-p, pixels, 3D, …many possibilities

- Magnetic Czochralski silicon
  - Standard industrial method of producing silicon
    - Cheap
    - Naturally high Oxygen content
      - more radiation hard?

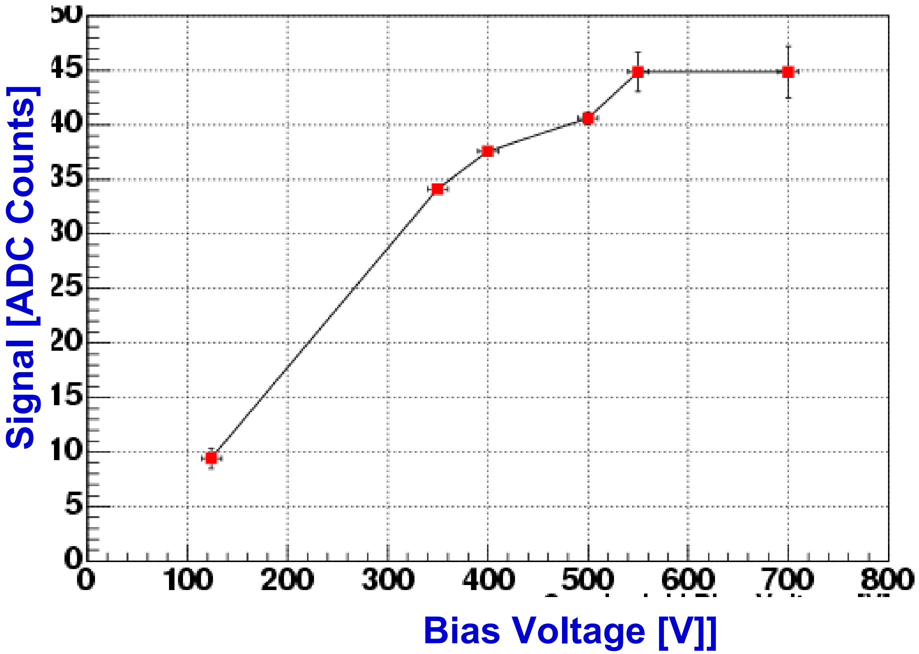
- Test beam at the CERN SPS of a MCz detector* before and after irradiation
  - LHC speed electronics (40 MHz) (3 SCTA (analogue) chips)
  - p$^+$-on-n MCz material
  - Area $_{\text{read out}}$ = 6.1 x 1.92 cm
  - 380 μm thick, 50 μm pitch



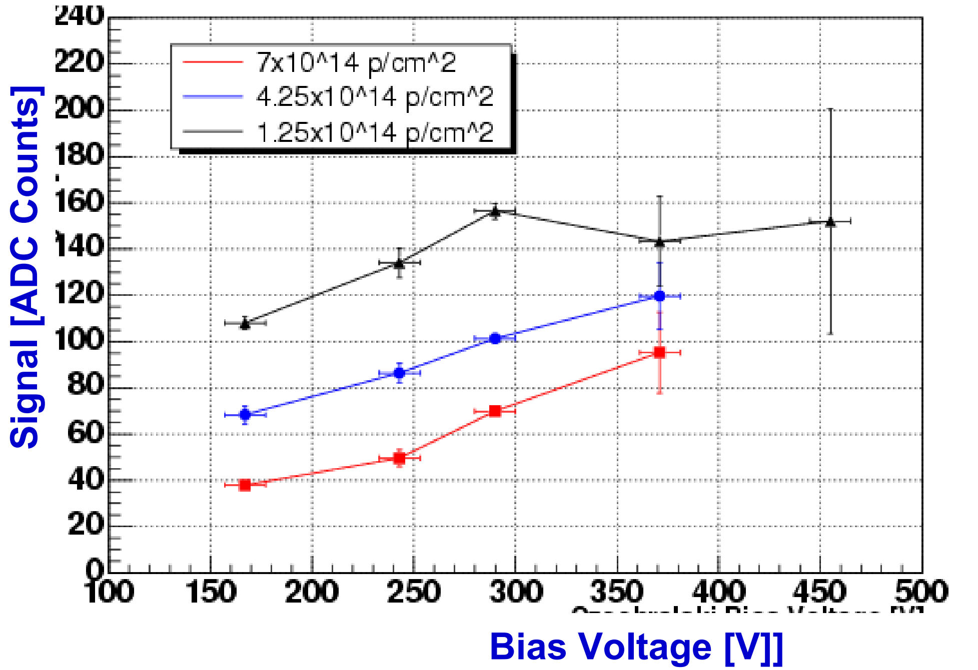
*Many thanks to the Helsinki Institute of Physics for the MCz detector

MCz test beam results

Unirradiated Detector



Irradiated Detector



✓ **Depleted the detector (~550 V)**

(CV measured Vdep ~ 420 V)

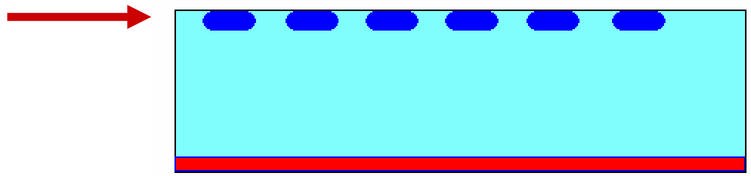
S / N > 23.5 + 2.5

(380 μm thick)

- 1.3 x 10^{14} 24 GeV p/cm^2 S/N = 15
- 4.3 x 10^{14} 24 GeV p/cm^2 S/N = 11 (under depleted)
- 7.0 x 10^{14} 24 GeV p/cm^2 S/N = 7 (under depleted)

Further MCz benefits

- The VELO currently uses n^+-on-n DOFZ silicon detectors



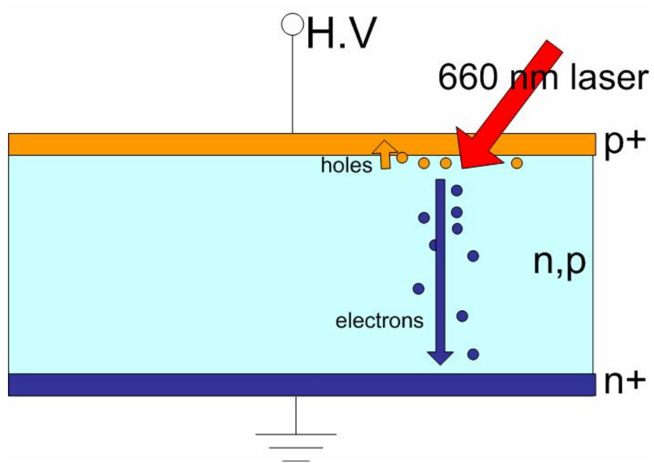
  - This is necessary because we want the silicon to have the high electric field always on the strip side in order to prevent loss of resolution and signal after *type inverision* and when operated *under-depleted*
  - However, n^+-on-n is expensive and restricts the choice of processing company (requires double-sided processing)

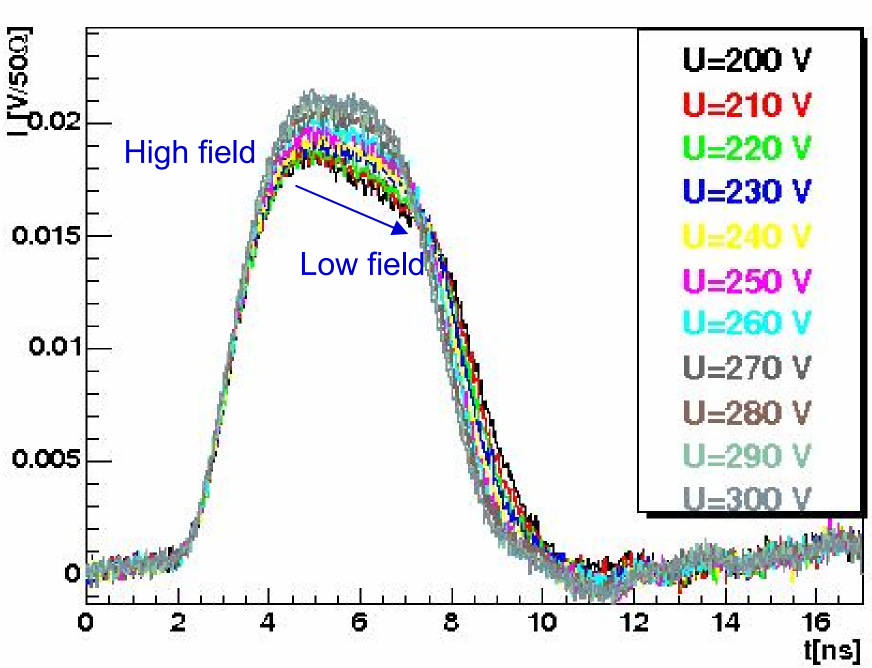
We have found that MCz **does not type invert** using the **Transient Current Technique** (measured to 5 x 10^{14} p/cm^2)

Transient Current Technique

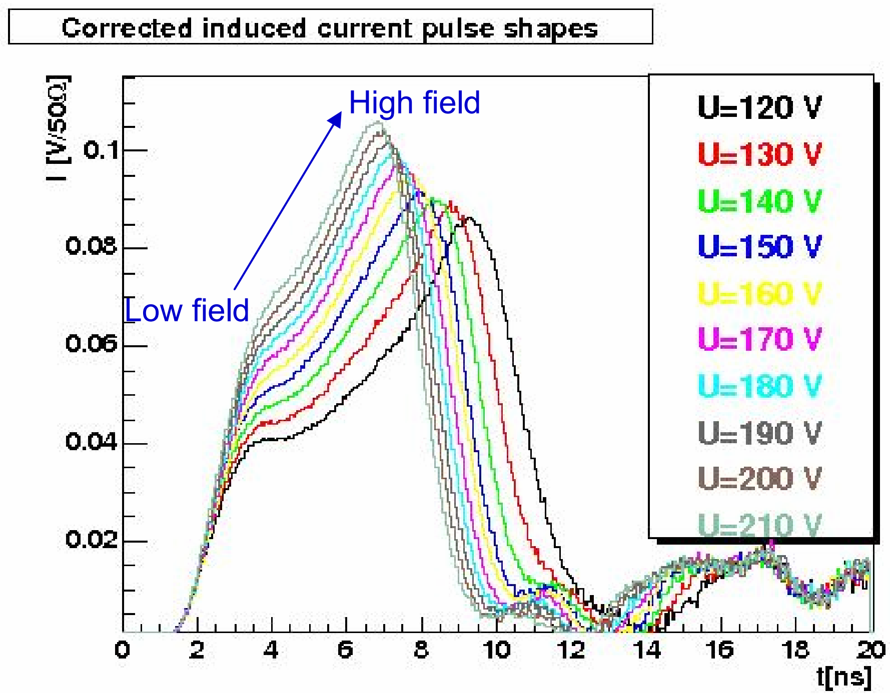
- experiment which probes the electric field inside the detectors

type inversion in FZ silicon



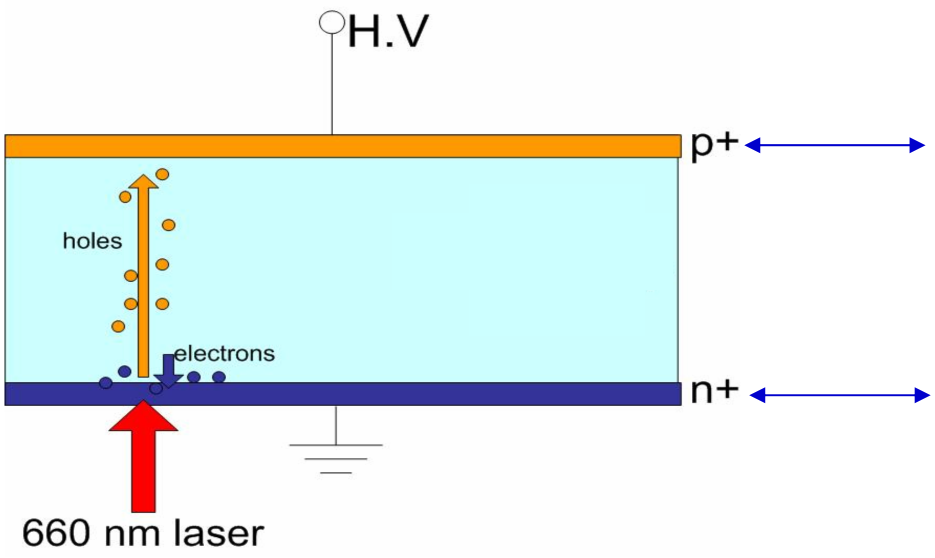


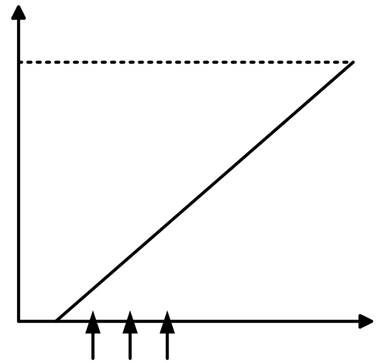
$\Phi = 1.74 \times 10^{13}$ 24 GeV/c p

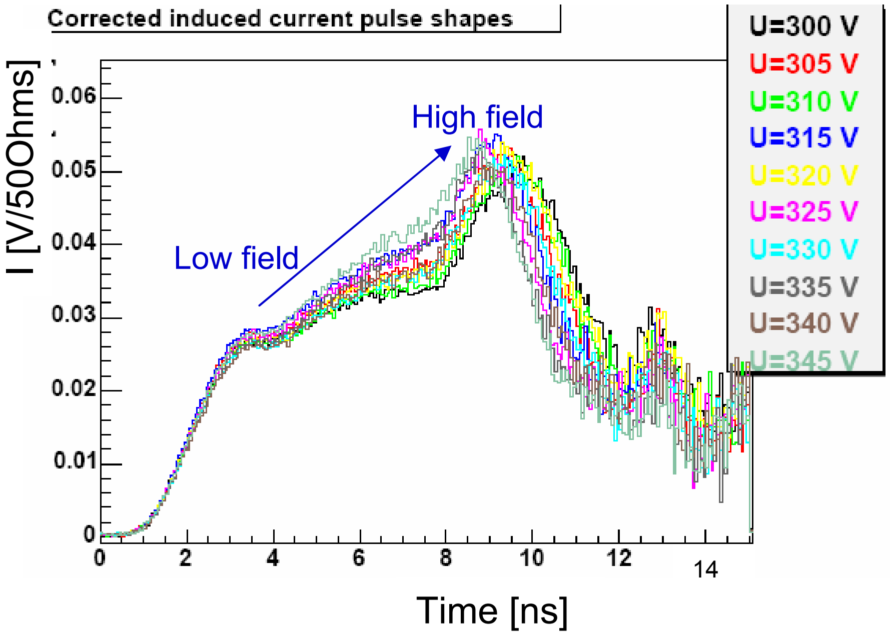


$\Phi = 3.61 \times 10^{14}$ 24 GeV/c p

TCT in MCz



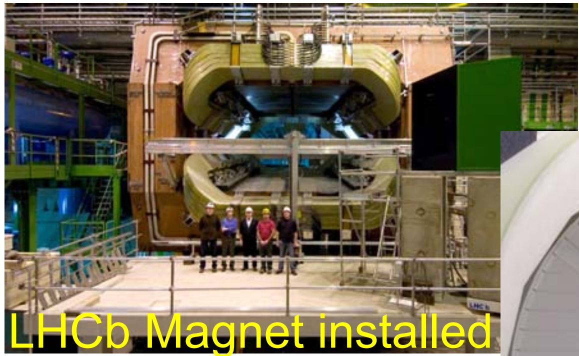


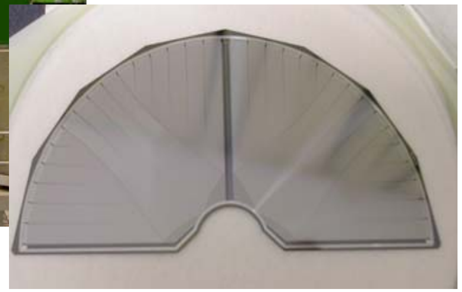


MCz silicon always has the high field on the strip side of the detector

=> standard p^+-on-n MCz detectors could replace the VELO n^+-on-n DOFZ silicon, however, further investigation of the radiation tolerance of MCz is required

Status & Conclusions





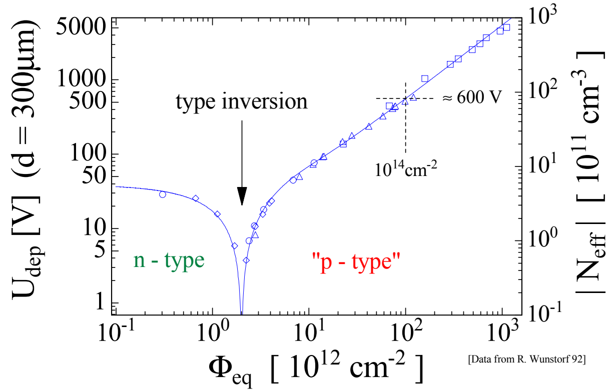
- The VELO is moving from the last prototype testing to sensor production
- Looking forward to physics in 2007
- Research started on upgrade possibilities for the LHCb detector
- There are many possibilities for the VELO silicon upgrade in 2010
  - n^+in-p FZ silicon
  - 3D detectors
  - Czochralski Silicon

first operation of full size MCz sensor with LHC speed electronics in test beam
- further test beam studies planned

non-inversion of MCz material under radiation demonstrated
- additional microscopic studies underway

Back Up Slides

A VELO story



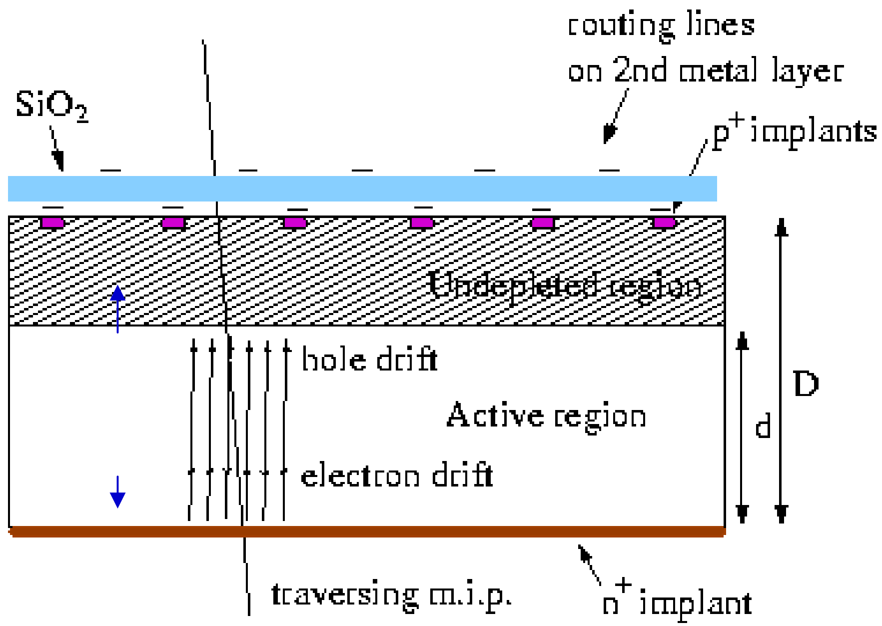
The standard silicon detectors are p⁺on-n silicon detectors.

Now consider what happens as the expt. proceeds and the radiation damage increases….

- Within the first few months the bulk material will still be n-type. The electric field grows from the front p^+ implant. The V_{fd} will be decreasing, hence no problems to deplete the sensor.

- Depending on the particle flux the bulk will eventually become p-type and the electric field will 'grow' from the back n^+ implant now. The V_{fd} is increasing every day hence at some point the detector will be operated under-depletion… in which case:

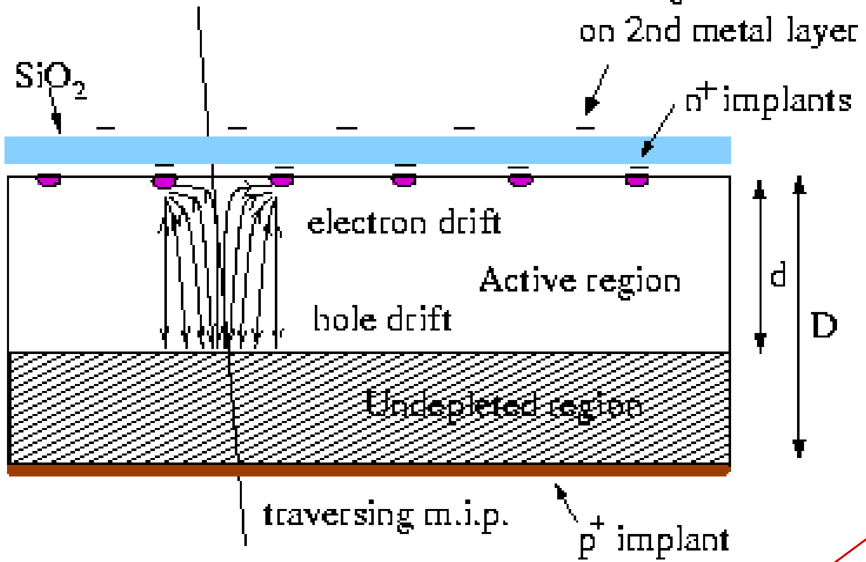
p^+on-n

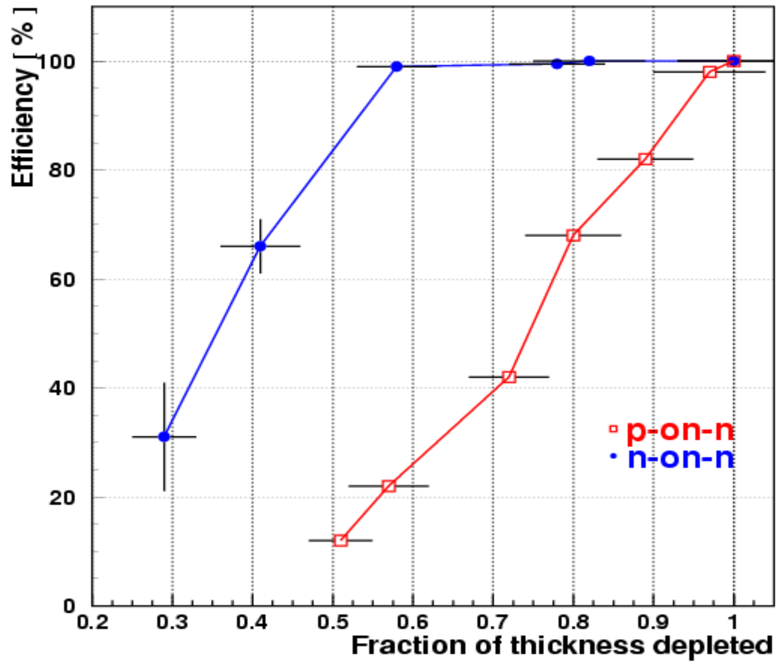


p-on-n silicon, under-depleted:

- Charge spread – degraded resolution
- Charge loss – reduced CCE

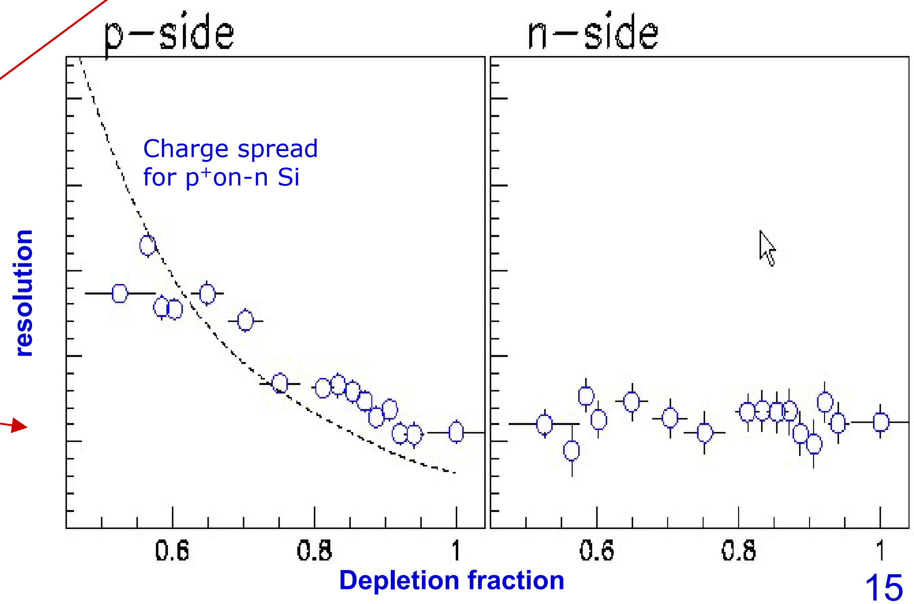
n^+on-n





n-on-n silicon, under-depleted:

- Limited loss in CCE
- Less degradation with under-depletion



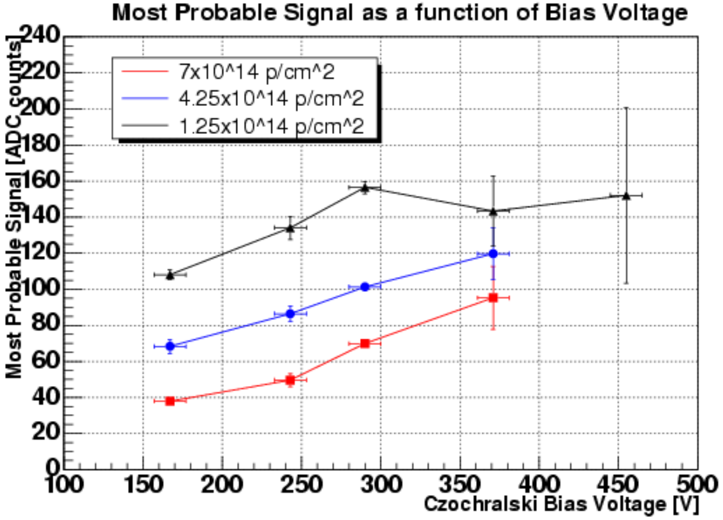
For LHCb n^+on-n detectors are the technology choice

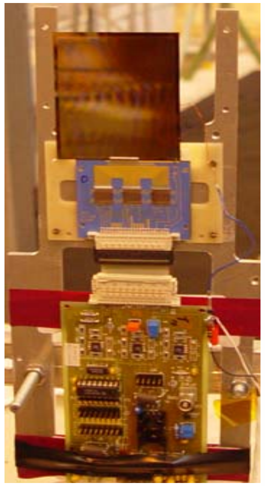
Radiation Hard Technologies

- Cz, n-on-p, 3D, or pixel technologies – Active UK R&D

Czochralski

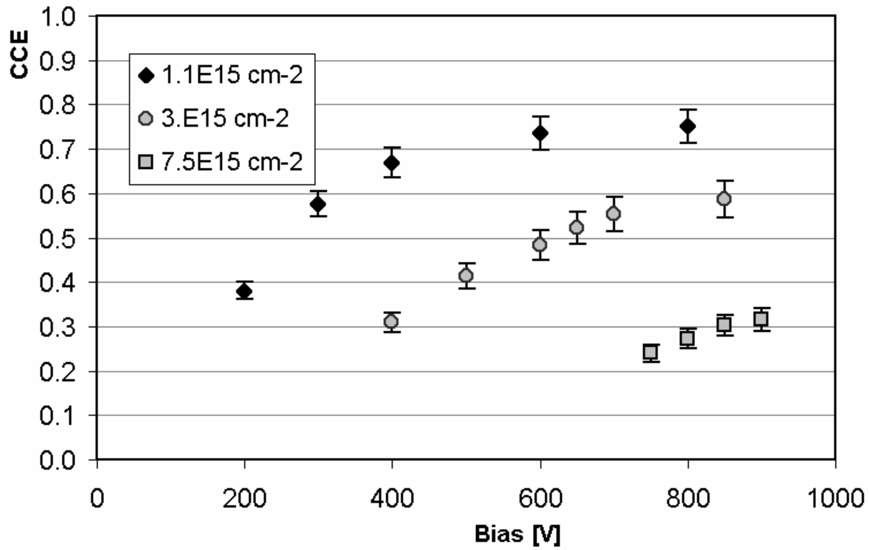
Glasgow, CERN

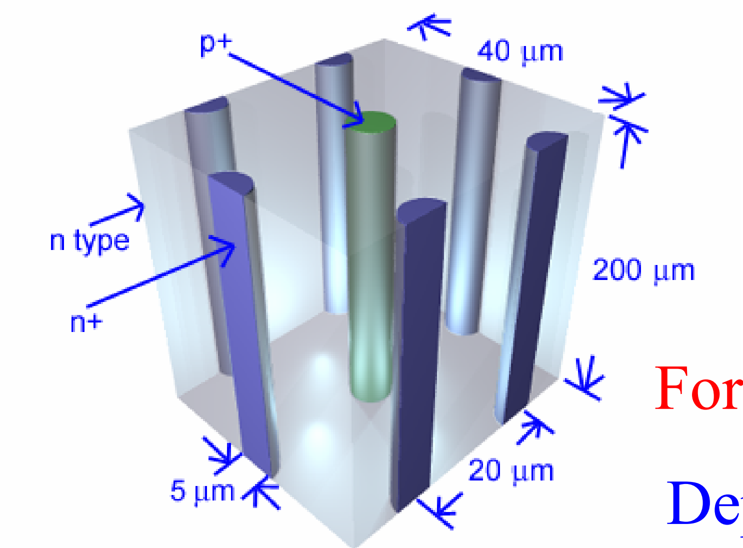




n-on-p

Liverpool





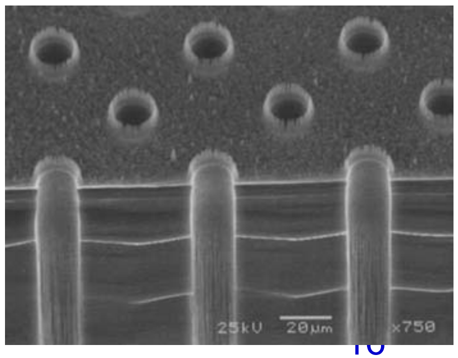
3D

Glasgow

Extreme rad. hard

For 4.5 x 10^{14} 24 GeV p/cm^2

Depletion voltage = 19V !!!



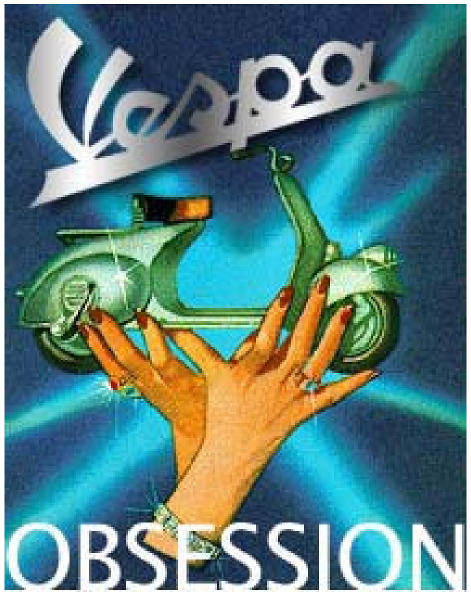
The VELO stories continue…VESPA

- VELO upgrade…

Suggested name only ☺

  - **VElo Superior Performance Apparatus***

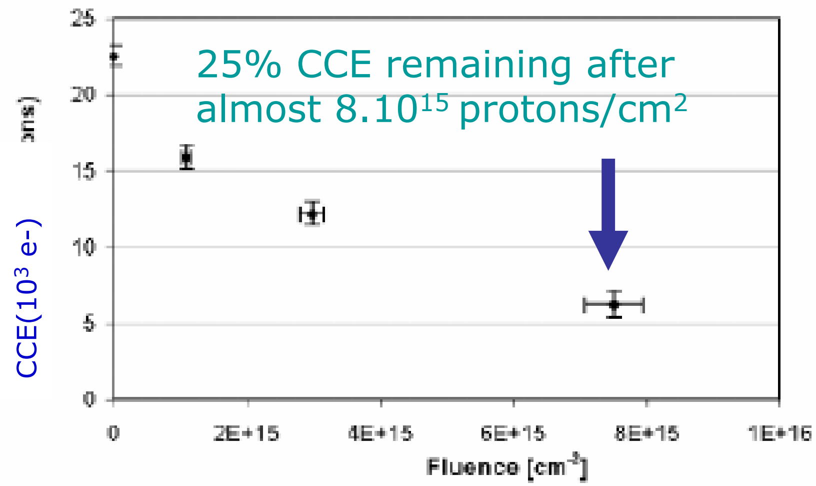
- Just build the same again..?
- Many possibilities for VELO improvement and not just silicon changes.
- Silicon possibilities
  - n^+on-p silicon
  - Magnetic Czochralski
  - 3D technology
  - Double sided
  - Strips or pixels?
  - …?



***Chris Parkes, LHCb UK Meeting. 6th July 2004**

p^+on-n, n^+on-n or n^+on-p?!

- p^+on-n
  - Advantages
    - Standard processing (cheaper)
  - Disadvantages
    - Charge loss and charge spread after bulk type inversion
- n^+on-n
  - Advantages
    - Operation under-depletion and after type inversion Electrons are collected instead of holes at the structured electrode and electrons are faster than holes -->less trapping
  - Disadvantages
    - Higher processing costs - requires double-sided imaging
- n^+on-p
  - Advantages
    - Electric field always at the same implant
    - No double sided processing required
    - Operation under-depletion and after type inversion results in limited CCE and resolution loss
  - Disadvantages
    - Bulk starts p-type*



*There is also an acceptor removal which can (for low fluences) be stronger than the acceptor creation. Thus depletion voltage can go slightly down before it increases again.

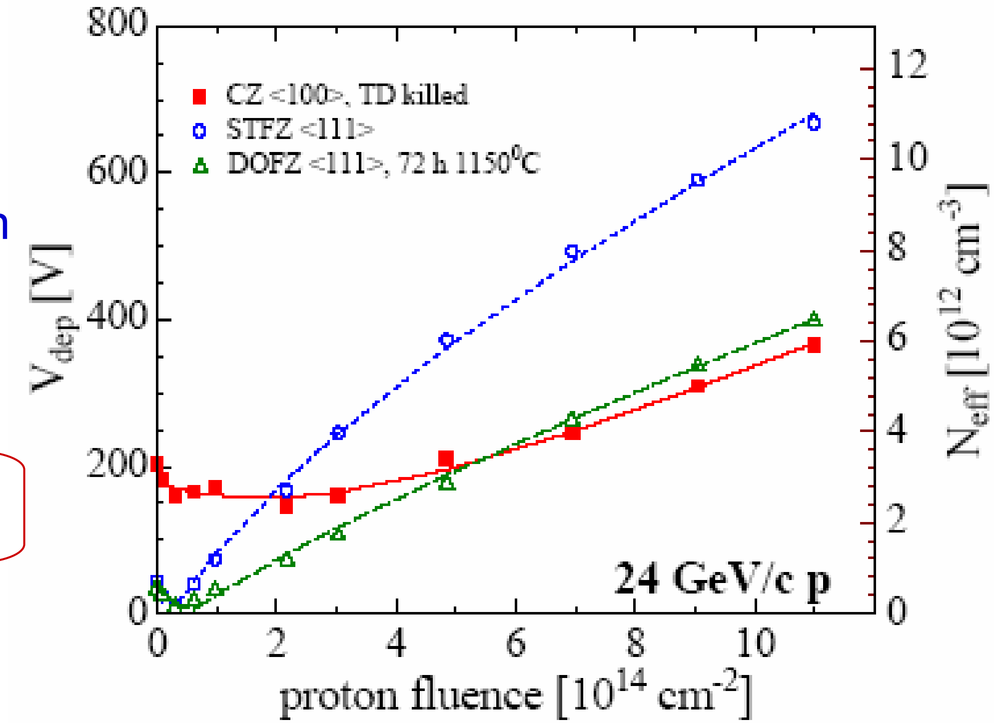
Plot from G. Casse, 4th RD50 Workshop, 5-7th May 2004.

MCz silicon

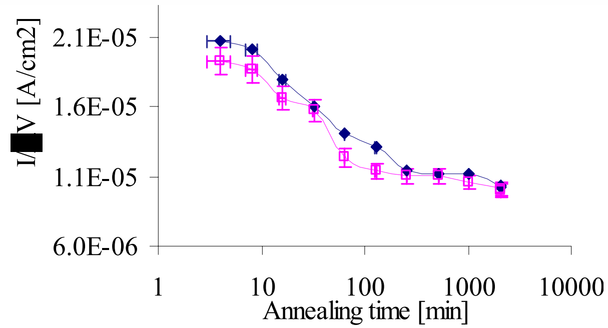
Czochralski silicon appears to behave differently from DOFZ and **FZ** silicon

- Surprises:
  - Many measurements have now shown MCz to be more radiation hard than DOFZ and FZ silicon
  - MCz does not follow the same macroscopic behaviour – does MCz type invert?

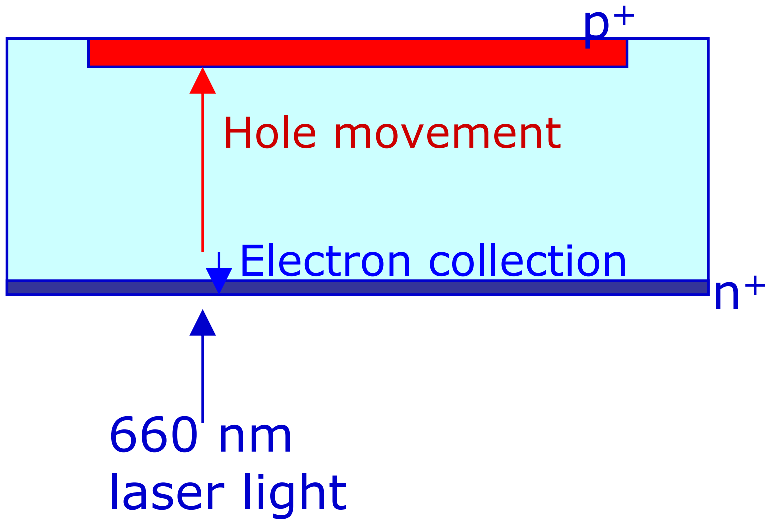
One of my studies…

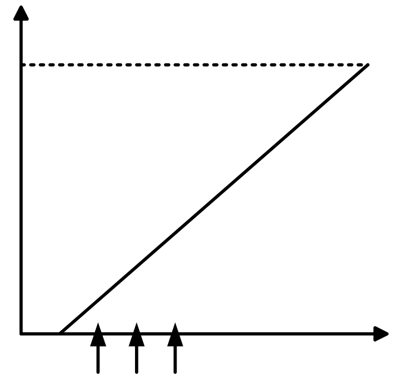


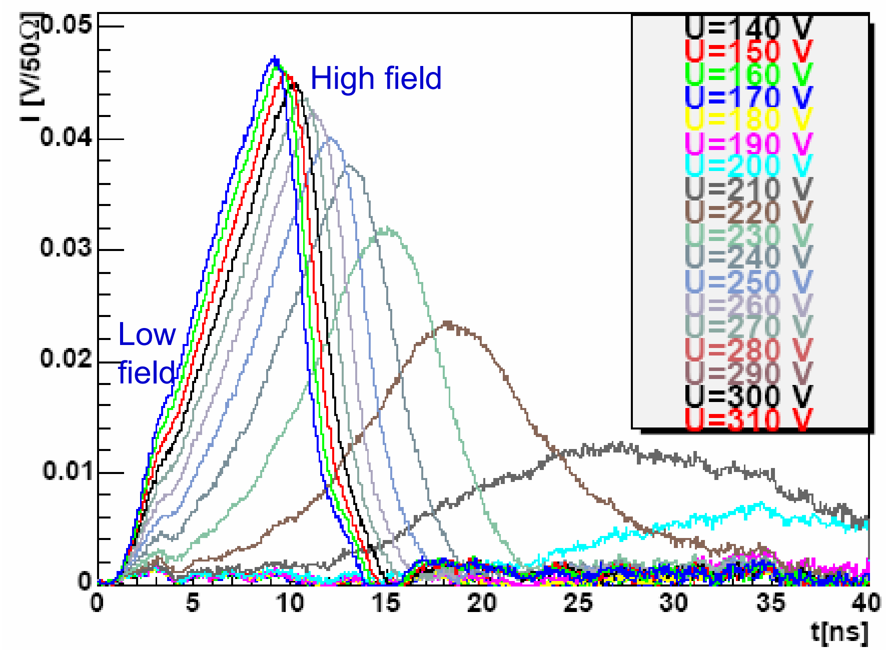
- Similarities:
  - Leakage current decreases with time after irradiation as usual
  - CCE behaviour no different



Transient Current Technique







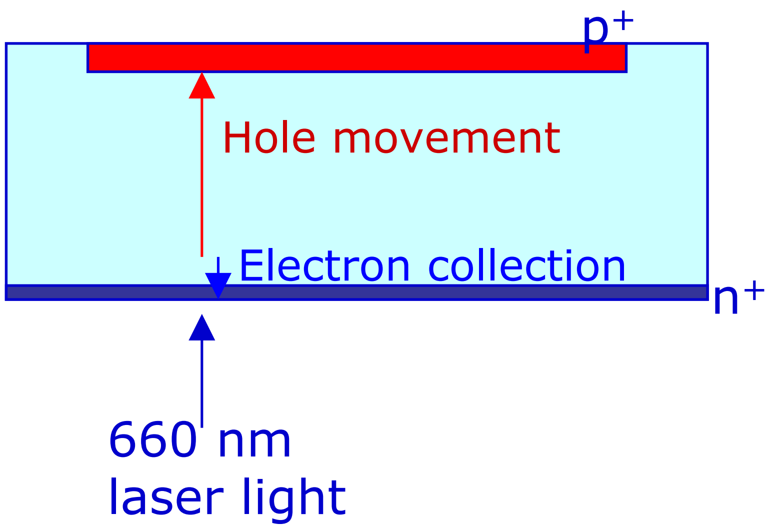
Experiment which probes the electric field inside the silicon detector

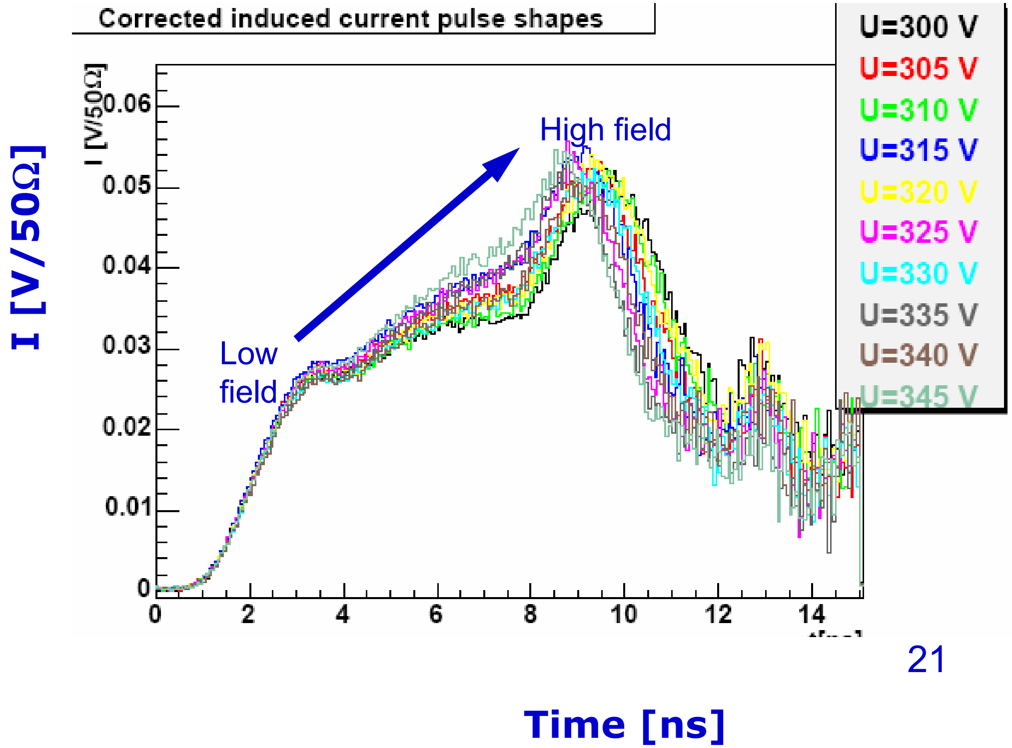
- Illuminate front (p^+) or rear (n^+) side of detector with 660 nm photons
- Light penetrates only a few μm depth
- Ramo's theorem dictates signal will be dominated by one type of charge carrier
- $\mathbf{I(t)=q\,E(\upsilon(t))\,\upsilon(t)_{drift}}$
- e.g. hole dominated curent (hole injection)
  - Illuminate rear (n^+) side of detector

MCz silicon

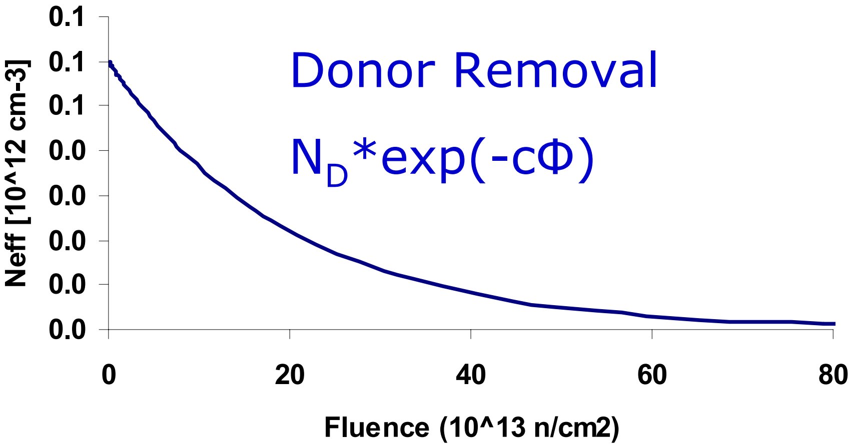
- After an irradiation level of $5x10^{14}$ p/cm^2, the high electric field was still at the front p^+ implant.

Hence MCz-Si had not type inverted.



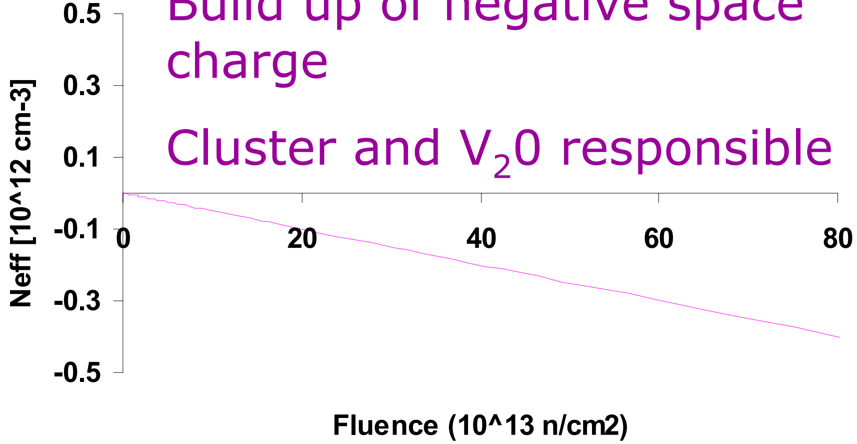


Resultant $|N_{eff}|$ shape



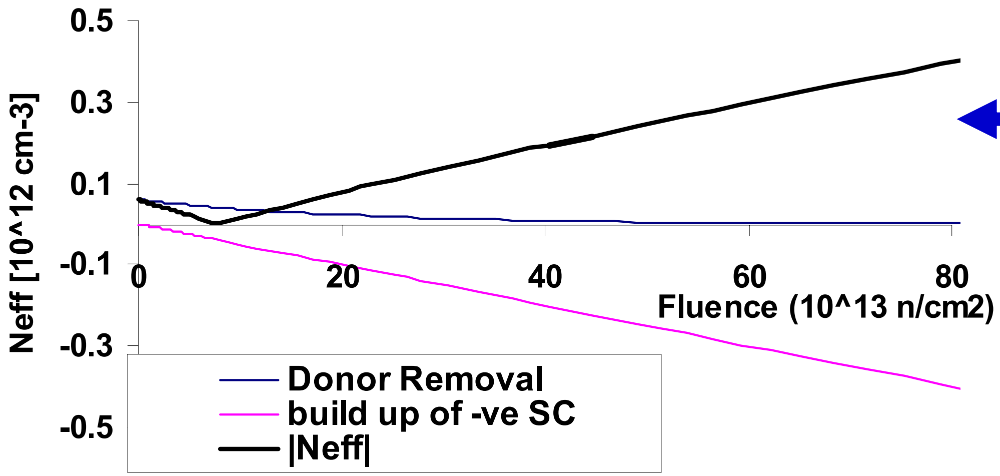
Donor Removal

N_D*exp(-cΦ)



Build up of negative space charge

Cluster and $V_2$0 responsible

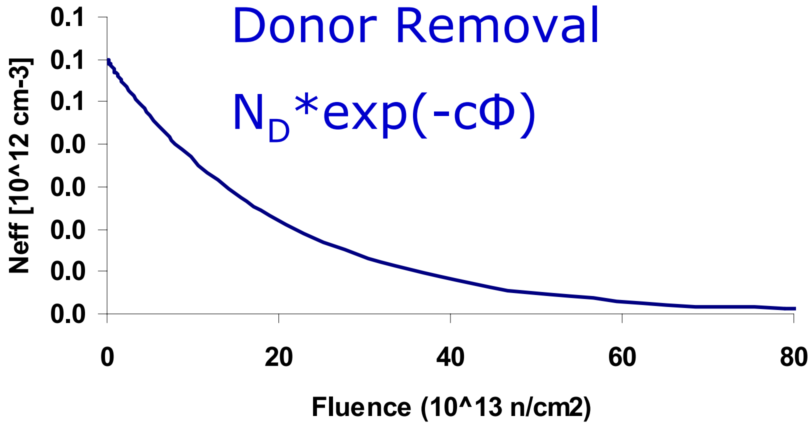


Resultant N_{eff} shape can be explained by the two processes

Resultant Cz $|N_{eff}|$ shape

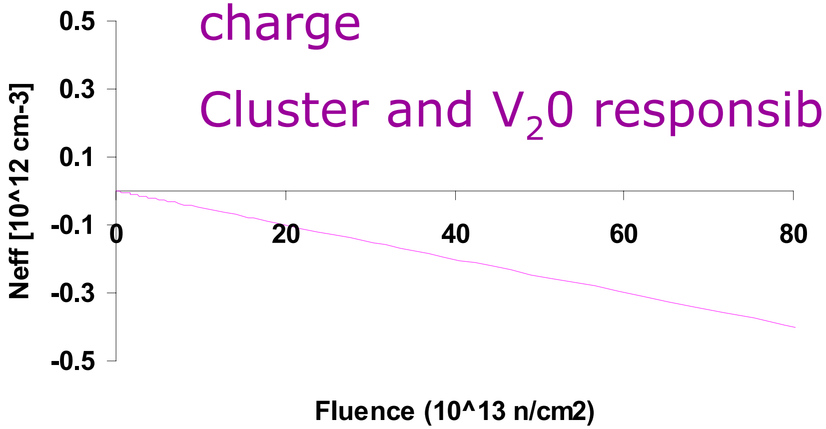
Donor Removal

N_D*exp(-cΦ)



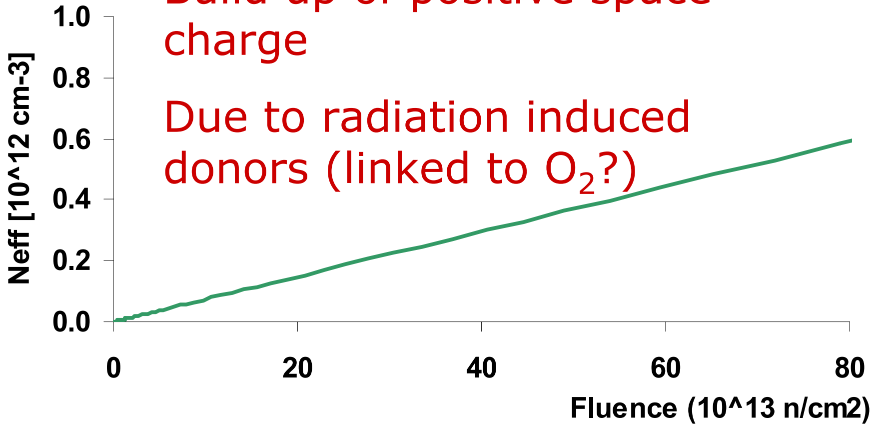
Build up of negative space charge

Cluster and V_20 responsible

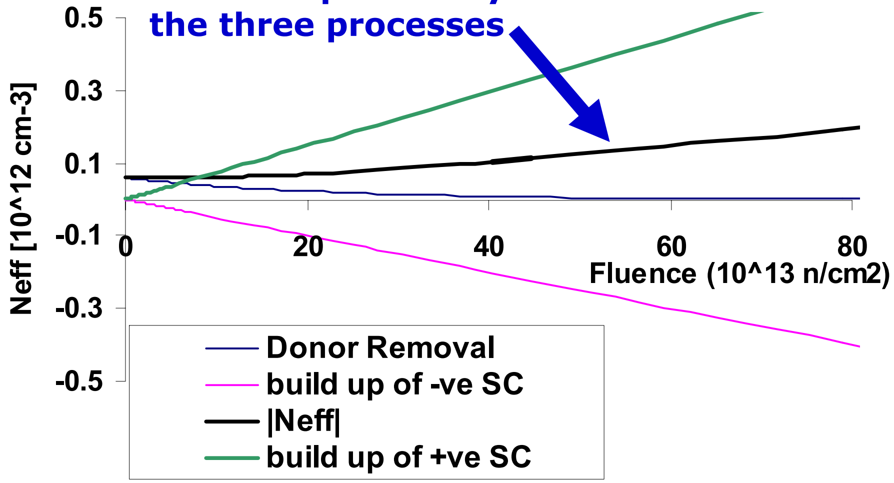


Build up of positive space charge

Due to radiation induced donors (linked to O_2?)

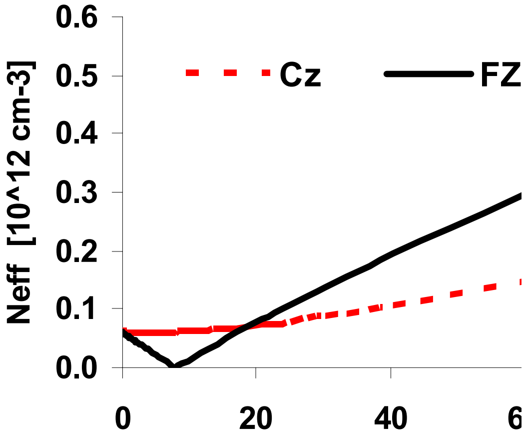


Resultant N_{eff} shape can be explained by the three processes



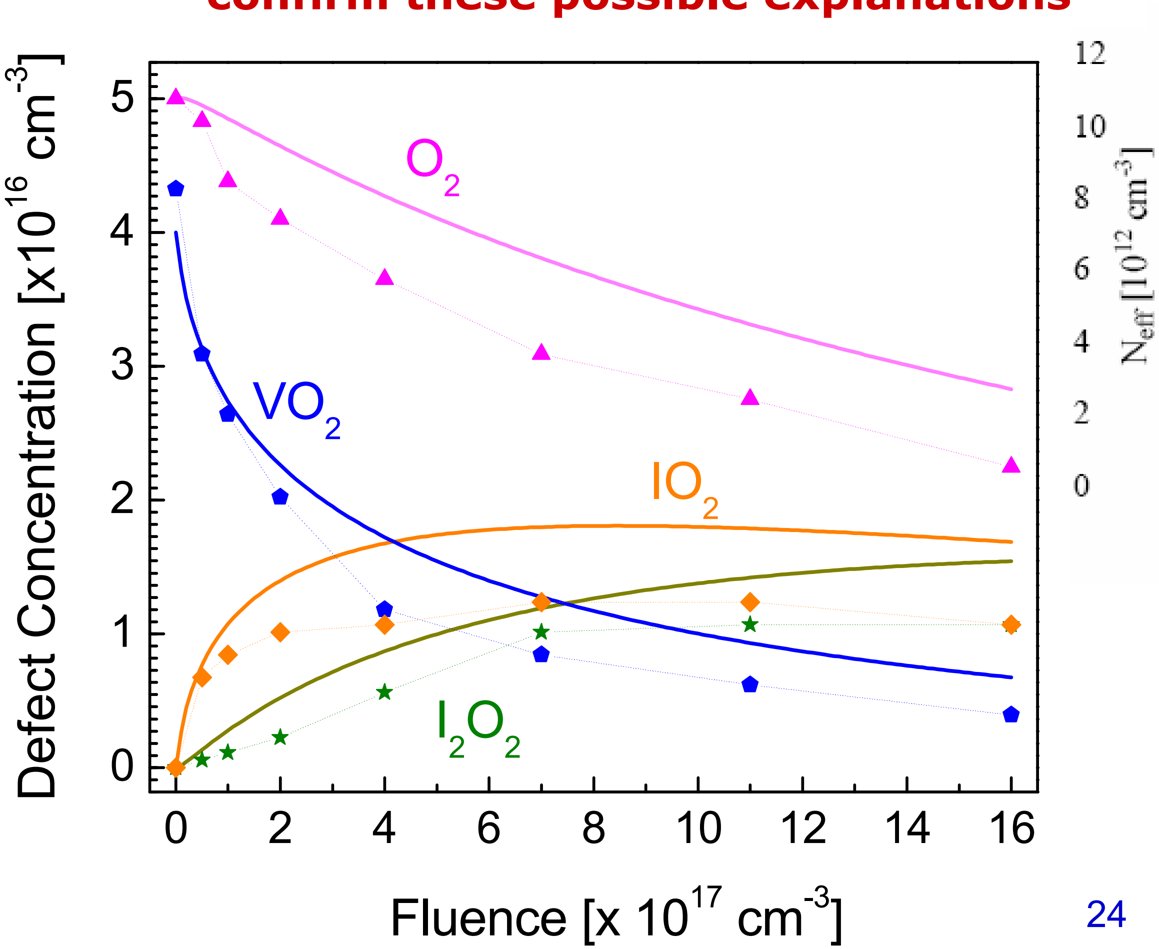
MCz has higher Oxygen content than FZ

Fz/Cz differences



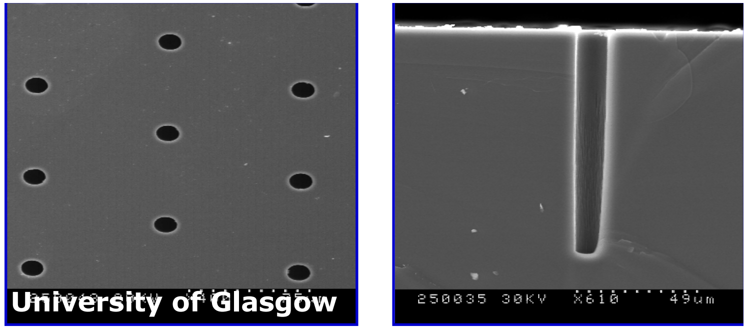
MCz

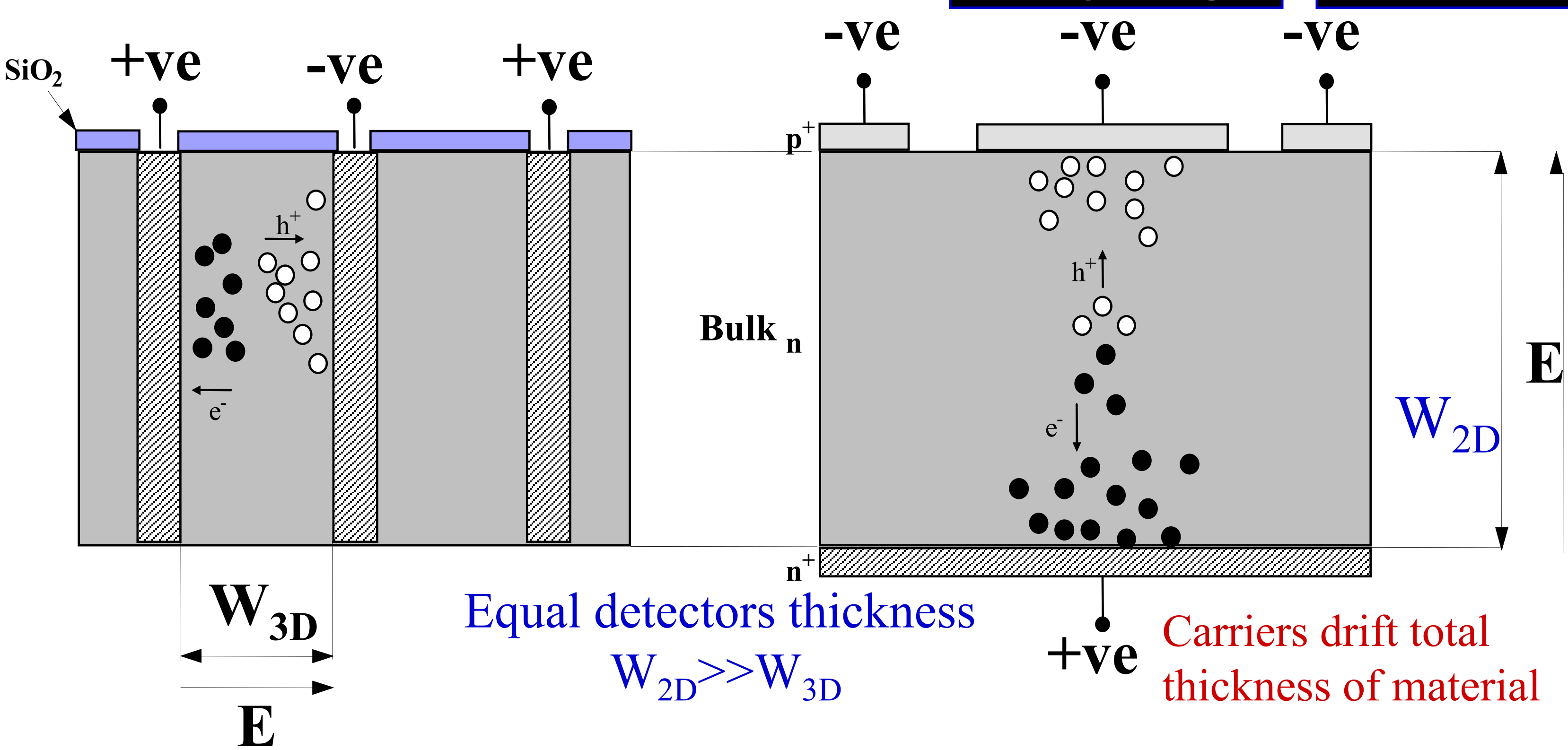
Lots of research into defects to confirm these possible explanations



J. L. Lindström, et. al., Physica B 308-310 (2001) 264

3D technologies



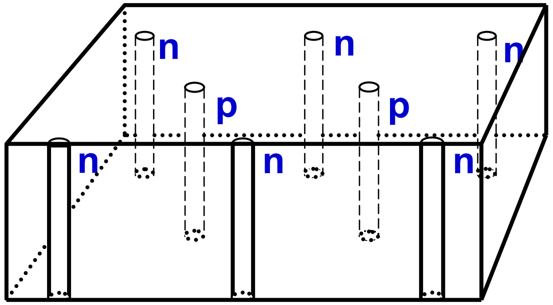


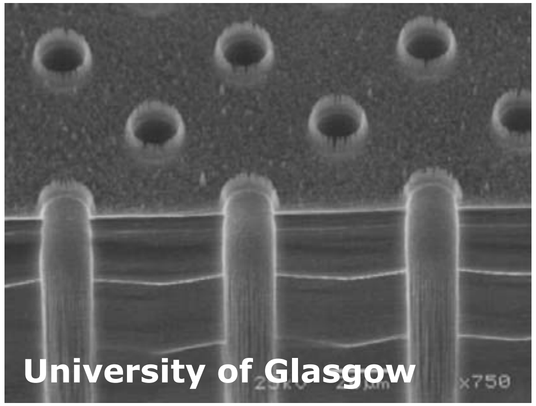
- **narrow columns along detector thickness-"3D"**
- **diameter:** 10µm **distance:** 50 - 100µm
  - Lateral depletion:
    - **lower depletion voltage needed**
    - **thicker detectors possible**
  - **fast signal**

$$V_{dep} = \frac{q_0}{2\varepsilon\varepsilon_0} \cdot |N_{eff}| \cdot d^2$$

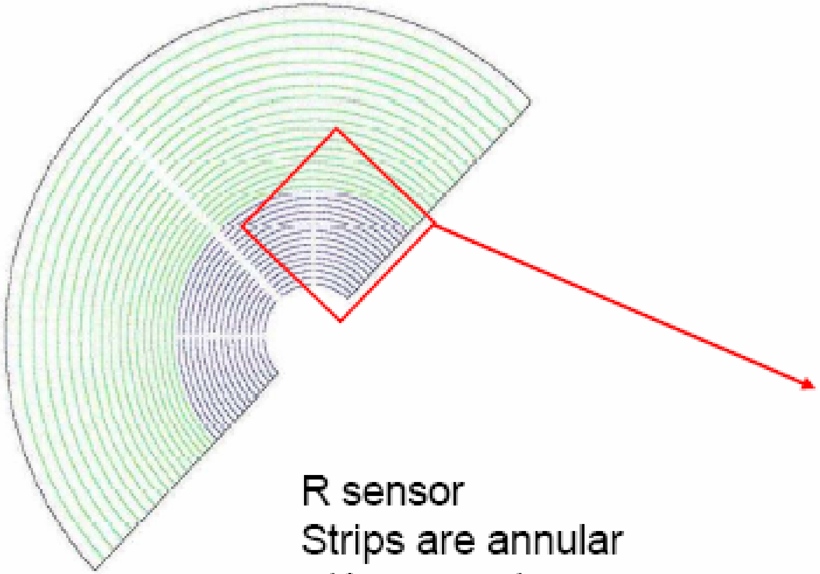
Idea proposed by S. Parker

3D VESPA



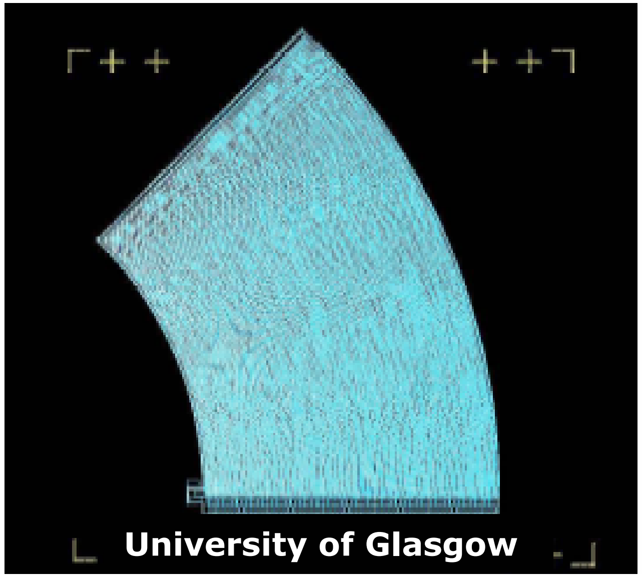


3D strip detectors : VELO design



3D device
Pitch varies linearly from 45μm at the innermost region to 90μm at strip 128.

R sensor
Strips are annular
π/4 segments
R = 8mm to R = 42mm
512 strips



Designed

Fabricated

Awaiting testing