Silicon sensor probing and radiation studies for the LHCb Silicon Tracker

Cristina Lois Gómez

Universidade de Santiago de Compostela

lois@physik.unizh.ch

LHCb Silicon Tracker group

On behalf of LHCb Silicon Tracker Group, ≈ 50 researchers from 6 institutes:

- Max-Planck-Institut für Kernphysik, Heidelberg
- Kiev Institute for Nuclear Research
- Laboratoire de Physique des Hautes Energies, Lausanne
- Budker Institute for Nuclear Physics, Novosibirsk
- Universidade de Santiago de Compostela
- Physik-Institut der Universität Zürich

Overview

- LHCb spectrometer and the Silicon Tracker

Overview

- LHCb spectrometer and the Silicon Tracker
- Sensor quality assurance program and results on first sensors

Overview

- LHCb spectrometer and the Silicon Tracker
- Sensor quality assurance program and results on first sensors
- Irradiation tests with IT prototype sensors

Overview

- LHCb spectrometer and the Silicon Tracker
- Sensor quality assurance program and results on first sensors
- Irradiation tests with IT prototype sensors
- Summary

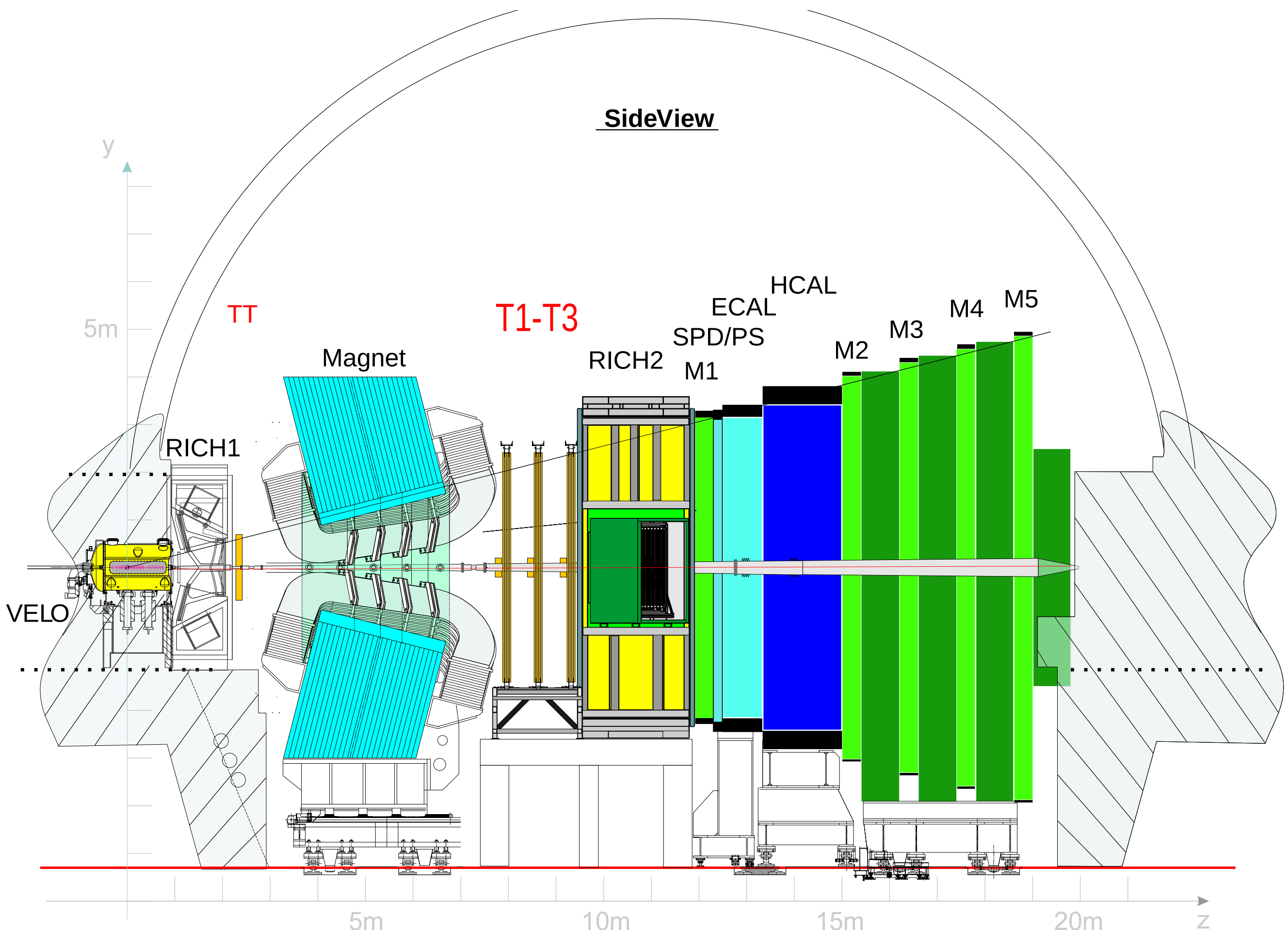
Overview

- LHCb spectrometer and the Silicon Tracker
- Sensor quality assurance program and results on first sensors
- Irradiation tests with IT prototype sensors
- Summary

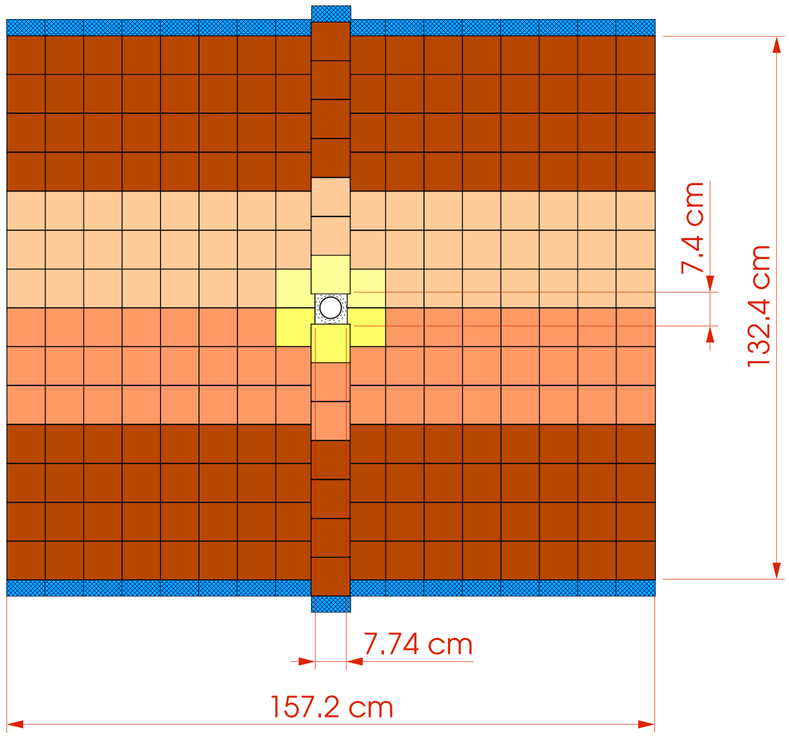
Overview

- LHCb spectrometer and the Silicon Tracker
- Sensor quality assurance program and results on first sensors
- Irradiation tests with IT prototype sensors
- Summary

LHCb spectrometer

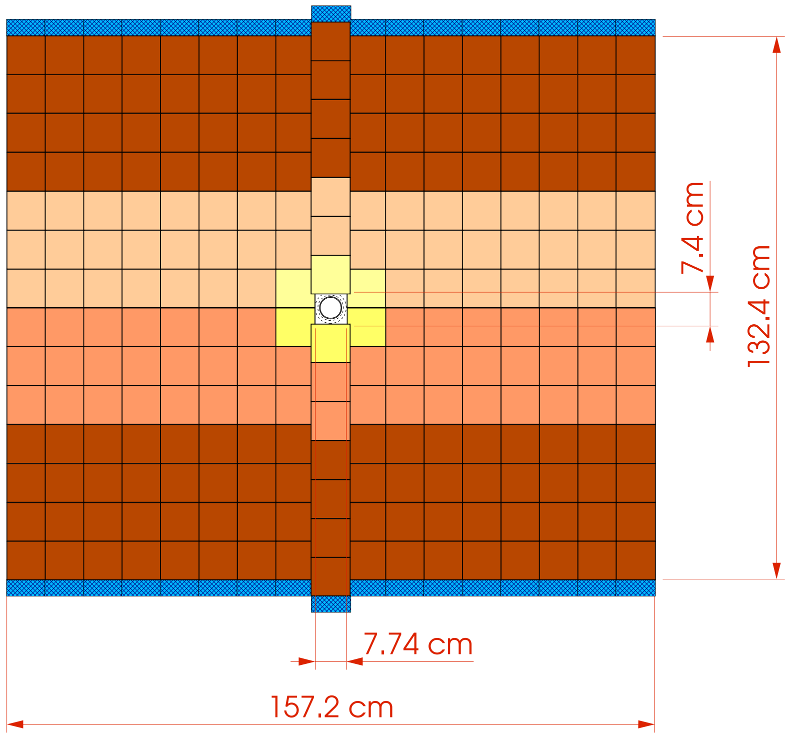


Trigger Tracker



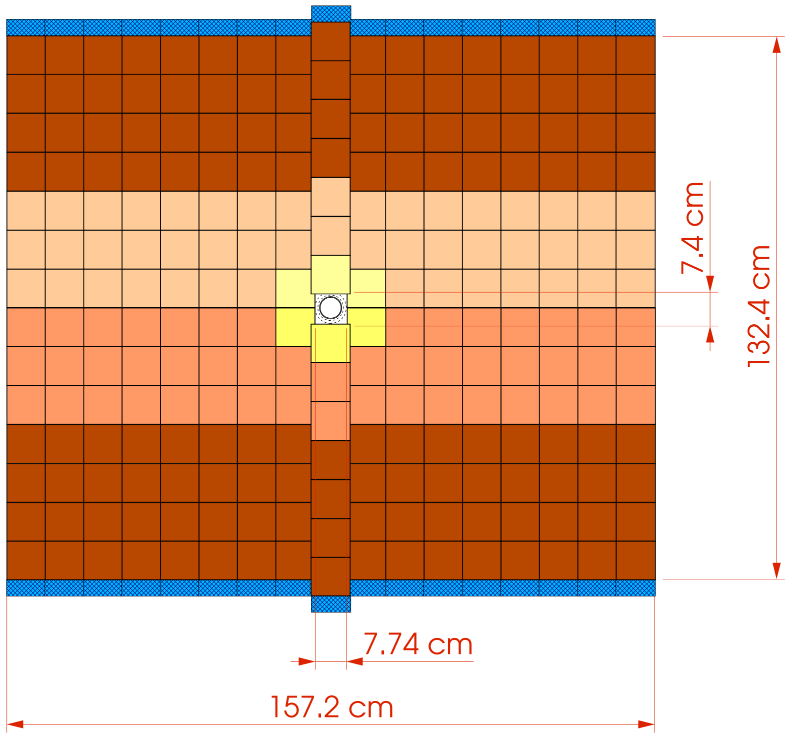
- 4 detection layers

Trigger Tracker



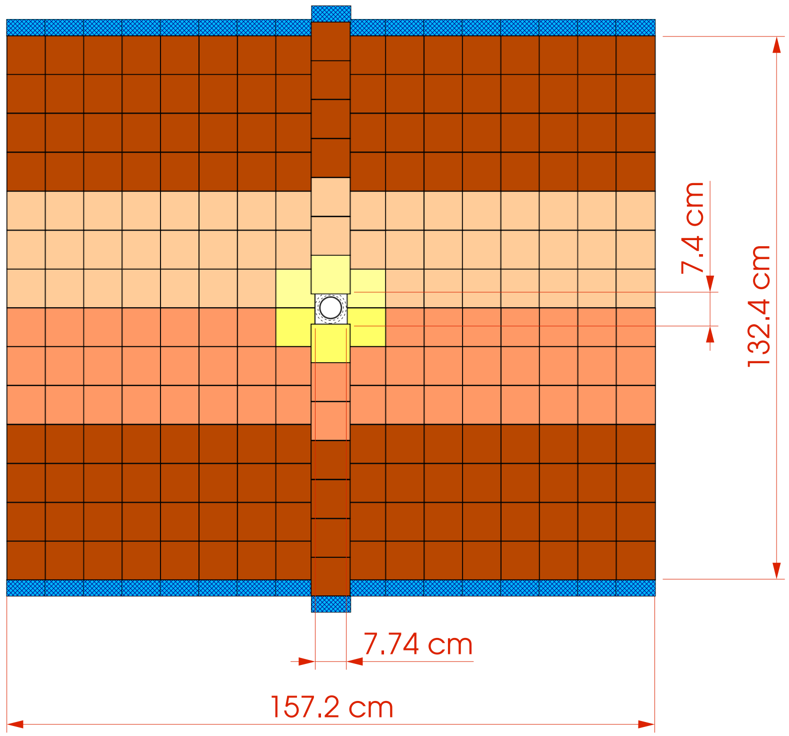
- 4 detection layers
- 14- and 7-sensor modules, several readout sectors

Trigger Tracker



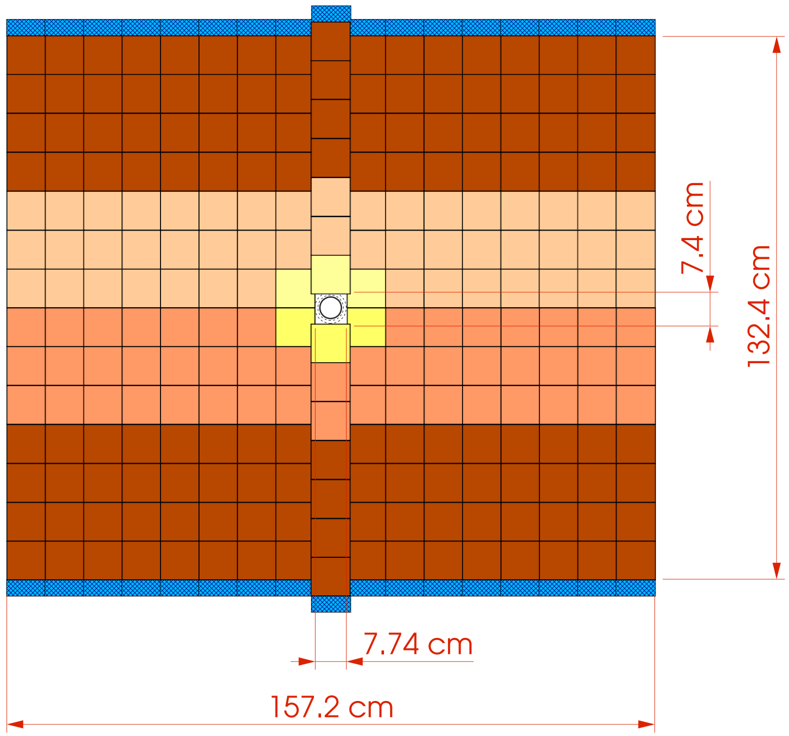
- 4 detection layers
- 14- and 7-sensor modules, several readout sectors
- all readout hybrids outside of acceptance

Trigger Tracker



- 4 detection layers
- 14- and 7-sensor modules, several readout sectors
- all readout hybrids outside of acceptance
- silicon microstrip detectors (HPK-500)

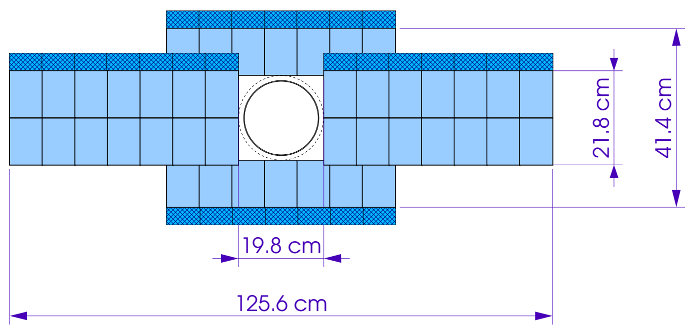
Trigger Tracker



- 4 detection layers
- 14- and 7-sensor modules, several readout sectors
- all readout hybrids outside of acceptance
- silicon microstrip detectors (HPK-500)
  - 500 μm thick
  - p-on-n, single-sided
  - 183 μm pitch, $w/p = 0.25$
  - dimensions 9.4×9.6 cm^2

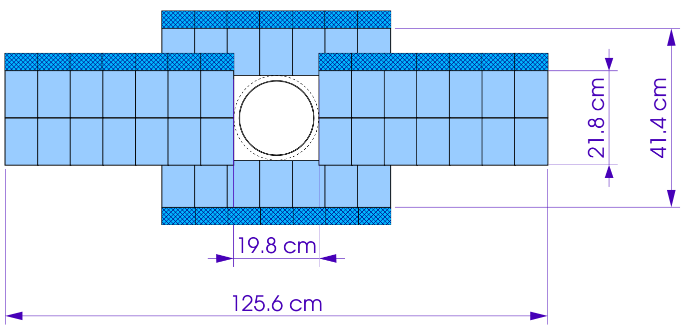
Inner Tracker

- 3 stations (T1-T3)

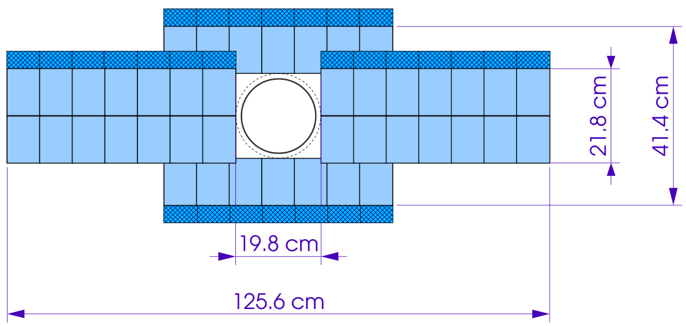


Inner Tracker

- 3 stations (T1-T3)
- 4 detection layers per station

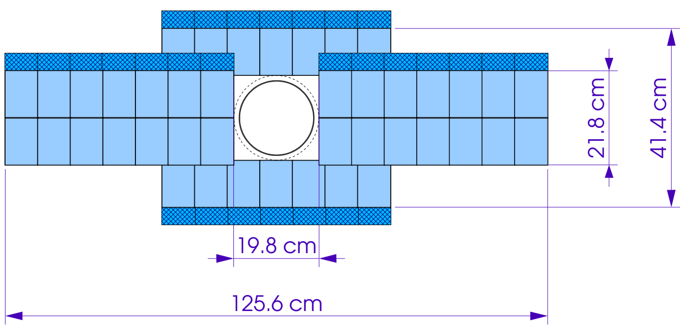


Inner Tracker



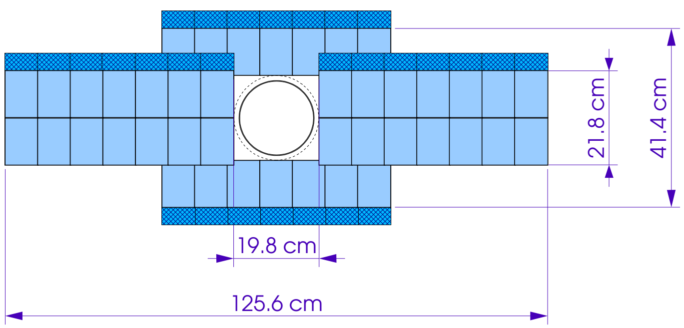
- 3 stations (T1-T3)
- 4 detection layers per station
- 4 individual boxes per station

Inner Tracker



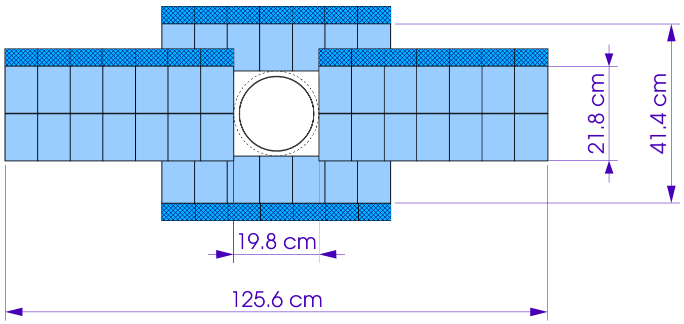
- 3 stations (T1-T3)
- 4 detection layers per station
- 4 individual boxes per station
- 1- and 2-sensor modules

Inner Tracker



- 3 stations (T1-T3)
- 4 detection layers per station
- 4 individual boxes per station
- 1- and 2-sensor modules
- silicon microstrip detectors (HPK-320, HPK-410)

Inner Tracker



- 3 stations (T1-T3)
- 4 detection layers per station
- 4 individual boxes per station
- 1- and 2-sensor modules
- silicon microstrip detectors (HPK-320, HPK-410)
  - 320 μm / 410 μm thick
  - p-on-n, single-sided
  - 198 μm pitch, $w/p = 0.25$
  - dimensions 11×7.8 cm^2

Overview

- LHCb spectrometer and the Silicon Tracker
- Sensor quality assurance program and results on first sensors
- Irradiation tests with IT prototype sensors
- Summary

Sensor quality assurance program

- Required to ensure excellent performance of modules

Sensor quality assurance program

- Required to ensure excellent performance of modules
- Results for first batches of sensors

Sensor quality assurance program

- Required to ensure excellent performance of modules
- Results for first batches of sensors

Sensor type	Delivered	Total production
HPK-320	14	194
HPK-410	35	386
HPK-500	98	1000

Sensor quality assurance program

- Required to ensure excellent performance of modules
- Results for first batches of sensors

Sensor type	Delivered	Total production
HPK-320	14	194
HPK-410	35	386
HPK-500	98	1000

- Two stages:

Sensor quality assurance program

- Required to ensure excellent performance of modules
- Results for first batches of sensors

Sensor type	Delivered	Total production
HPK-320	14	194
HPK-410	35	386
HPK-500	98	1000

- Two stages:
  - tests performed by HPK prior to shipment

Sensor quality assurance program

- Required to ensure excellent performance of modules

- Results for first batches of sensors

Sensor type	Delivered	Total production
HPK-320	14	194
HPK-410	35	386
HPK-500	98	1000

- Two stages:
  - tests performed by HPK prior to shipment
  - tests performed by our group after reception

Tests performed by the ST group

Tests performed by the ST group

- Visual inspection

Tests performed by the ST group

- Visual inspection
- IV curves

Tests performed by the ST group

- Visual inspection
- IV curves
- CV curves

Tests performed by the ST group

- Visual inspection
- IV curves
- CV curves
- Metrological measurements

Tests performed by the ST group

- Visual inspection
- IV curves
- CV curves
- Metrological measurements
- Other tests

Tests performed by the ST group

- Visual inspection
- IV curves
- CV curves
- Metrological measurements
- Other tests

Visual inspection

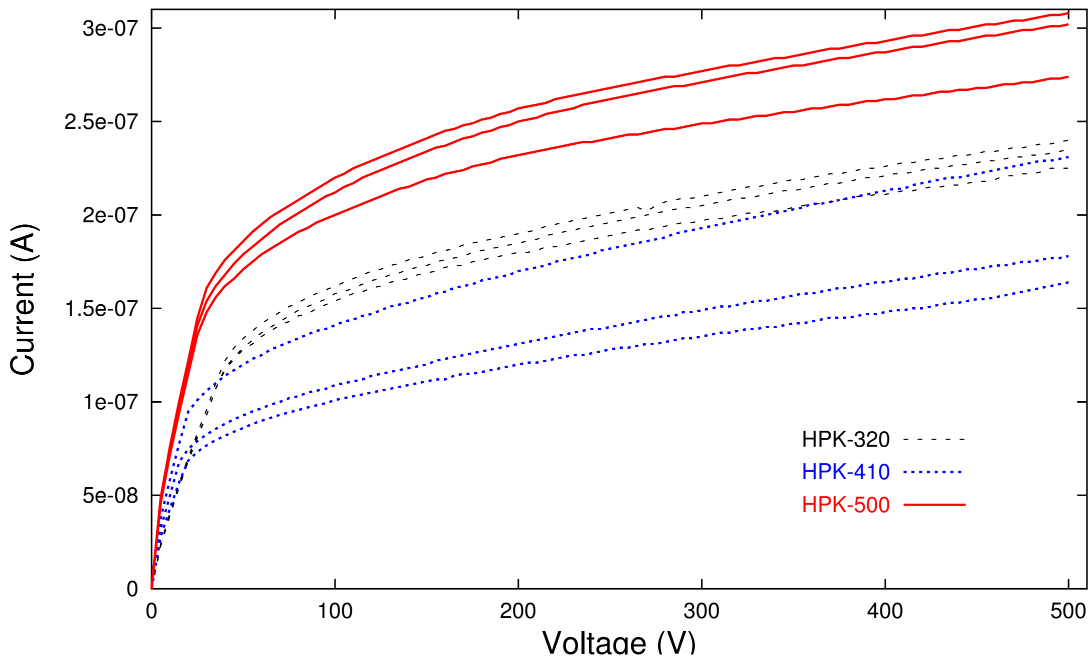
- Examine sensors under microscope:
  - take note of scratches/defects
  - look for chipped edges
  - look for pad bondability/contamination
  - check serial # on scratch-pad

Visual inspection

- Examine sensors under microscope:
  - take note of scratches/defects
  - look for chipped edges
  - look for pad bondability/contamination
  - check serial # on scratch-pad
- sensors very good: no deep scratches or big defects found

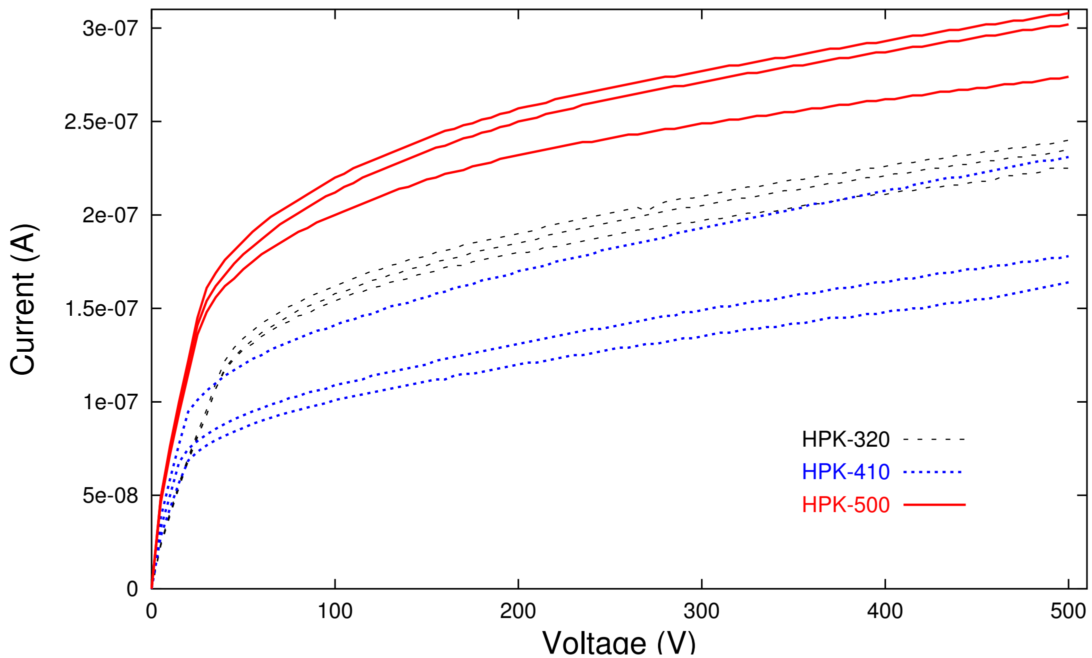
Leakage Currents

- IV curves taken up to 500 V, at T∼20 °C, RH $< 30\%$



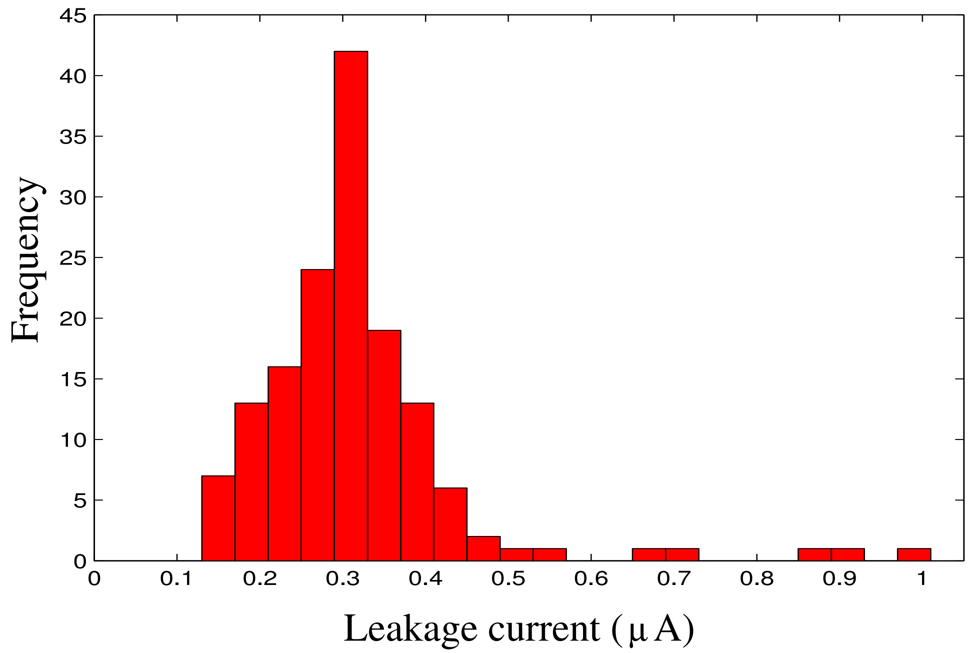
Leakage Currents

- IV curves taken up to 500 V, at T∼20 °C, RH $< 30\%$
- Great uniformity in currents; no breakdown below 500 V



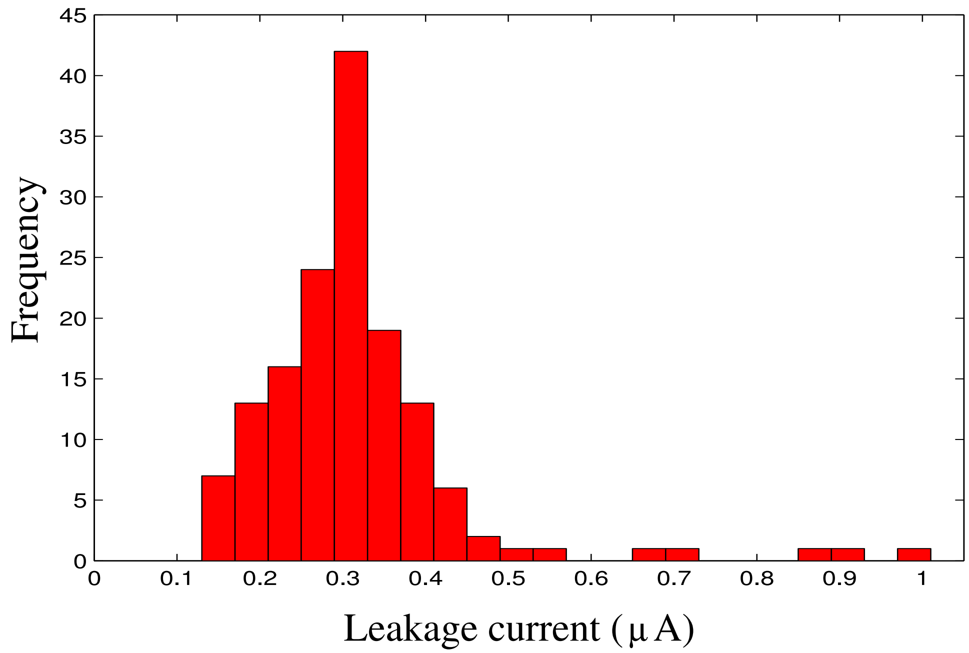
Leakage Currents

- Observed low currents; typically $I < 400$ nA at 500 V



Leakage Currents

- Observed low currents; typically $I < 400$ nA at 500 V
- All sensors fulfill specifications

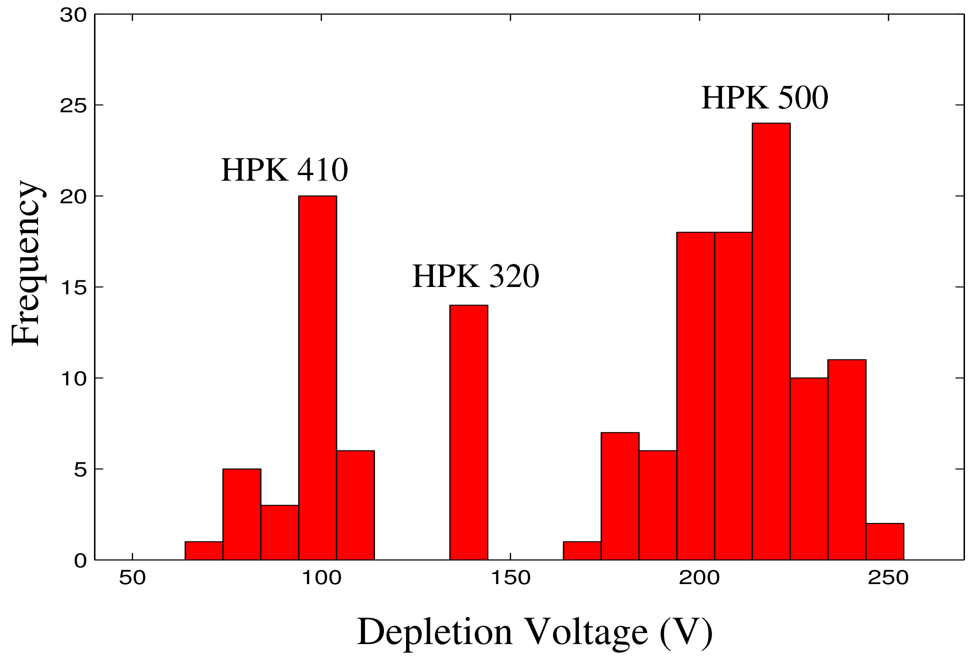


Full depletion voltage

- CV curves taken at T∼20 °C, RH $< 30\%$, $f = 1$ kHz

Full depletion voltage

- CV curves taken at T∼20 °C, RH $< 30\%$, $f = 1$ kHz
- All sensors fulfill specifications



Metrology measurements

- optical metrology machine
  Mahr OMS 600

Metrology measurements

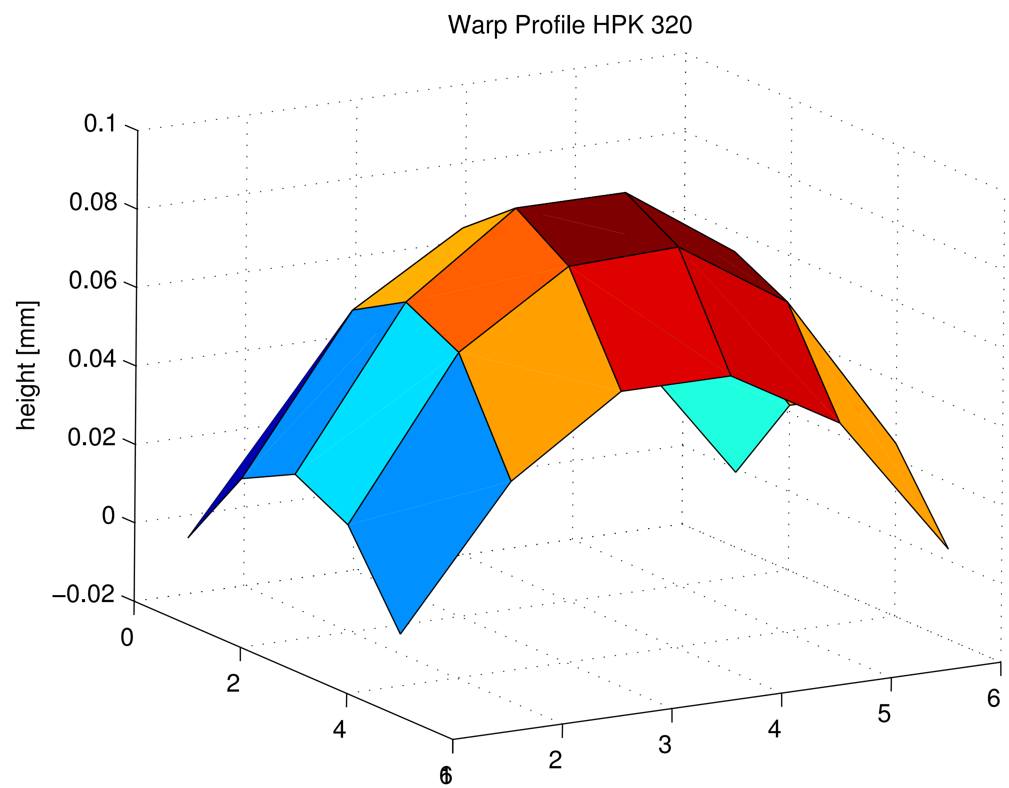
- optical metrology machine Mahr OMS 600
- flatness, length, width, parallelity, etc.

Metrology measurements

- optical metrology machine Mahr OMS 600
- flatness, length, width, parallelity, etc.
- All sensors very good

Metrology measurements

- optical metrology machine Mahr OMS 600
- flatness, length, width, parallelity, etc.
- All sensors very good



Other tests

- Coupling capacitances

Other tests

- Coupling capacitances
- Other features of leakage currents:

Other tests

- Coupling capacitances
- Other features of leakage currents:
  - Dependence on mechanical strain

Other tests

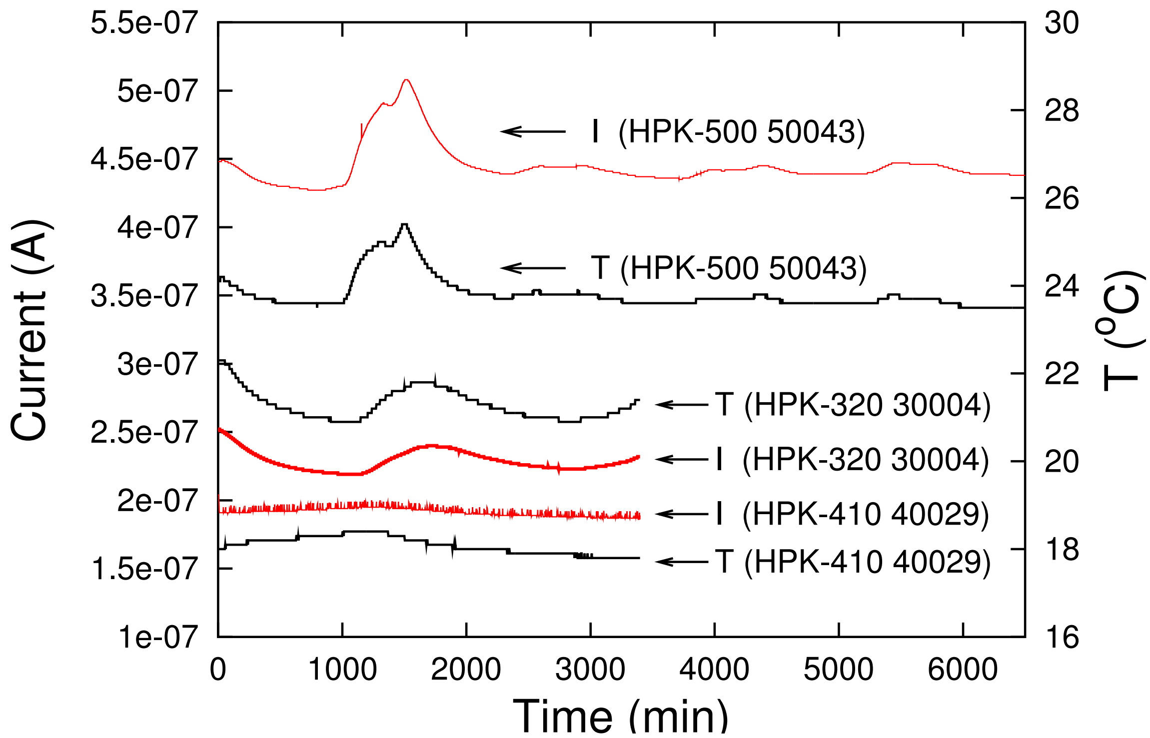
- Coupling capacitances
- Other features of leakage currents:
  - Dependence on mechanical strain
  - Reproducibility

Other tests

- Coupling capacitances
- Other features of leakage currents:
  - Dependence on mechanical strain
  - Reproducibility
  - Stability over $\sim$24 h

Other tests

- Coupling capacitances
- Other features of leakage currents:
  - Dependence on mechanical strain
  - Reproducibility
  - Stability over ∼24 h



Overview

- LHCb spectrometer and the Silicon Tracker
- Sensor quality assurance program and results on first sensors
- Irradiation tests with IT prototype sensors
- Summary

Irradiated Sensors

- 3 IT Multi-Geometry prototype sensors (5 regions; same thickness, dimensions and material characteristics as HPK-320)

Irradiated Sensors

- 3 IT Multi-Geometry prototype sensors (5 regions; same thickness, dimensions and material characteristics as HPK-320)

- 1 CMS-OB2 test-structure (monitor diode, mini-detector, isolated elements of strips, polysilicon, coupling capacitances,...)

Irradiation

- T7 irradiation facility, at PS at CERN

Irradiation

- T7 irradiation facility, at PS at CERN
- 24 GeV/c protons; hardness $k = 0.6$

Irradiation

- T7 irradiation facility, at PS at CERN
- 24 GeV/c protons; hardness $k = 0.6$
- Fluences:
  - One sensor: 1.9×10^{13} p/cm^2 (~ 7 years innermost IT)
  - Remaining: 6.3×10^{13} p/cm^2 (~ 20 years innermost IT)

Irradiation

- T7 irradiation facility, at PS at CERN
- 24 GeV/c protons; hardness $k = 0.6$
- Fluences:
  - One sensor: 1.9×10^{13} p/cm^2 (~ 7 years innermost IT)
  - Remaining: 6.3×10^{13} p/cm^2 (~ 20 years innermost IT)
- Proton fluences from aluminium foils activation measurements

Irradiation

- T7 irradiation facility, at PS at CERN
- 24 GeV/c protons; hardness $k = 0.6$
- Fluences:
  - One sensor: 1.9×10^{13} p/cm^2 (~ 7 years innermost IT)
  - Remaining: 6.3×10^{13} p/cm^2 (~ 20 years innermost IT)
- Proton fluences from aluminium foils activation measurements
- Annealing of 80 min at 60°C

Electrical characterization

- Performed at room temperature; between measurements, -20°C

Electrical characterization

- Performed at room temperature; between measurements, -20°C
- Measured:
  - full depletion voltages
  - leakage currents $\longrightarrow$ current related damage constant α
  - AC- and DC- strip tests: strip capacitances, inter-strip capacitances, coupling capacitances, strip currents

Full depletion voltages

- Extracted from total sensor capacitance

Sensor	Fluence (p/cm^{-2})	$V depl$ (V) before	$V depl$ (V) after
LHCb 5	1.9×10^{13}	55	40
LHCb 8	6.3×10^{13}	55	130
LHCb 1	6.3×10^{13}	55	130
Diode	6.3×10^{13}	120	115

Full depletion voltages

- Extracted from total sensor capacitance

Sensor	Fluence (p/cm^{-2})	$V depl$ (V) before	$V depl$ (V) after
LHCb 5	1.9×10^{13}	55	40
LHCb 8	6.3×10^{13}	55	130
LHCb 1	6.3×10^{13}	55	130
Diode	6.3×10^{13}	120	115

$\Rightarrow$ After lower fluence, depletion voltage lower than initial

Leakage currents

- After irradiation $\Delta I = \alpha V \phi$

Leakage currents

- After irradiation $\Delta I = \alpha V \phi$
- Calculate the current related damage constant α

Leakage currents

- After irradiation $\Delta I = \alpha V \phi$
- Calculate the current related damage constant α
- Use I at $V_{bias} = V_{depl.}$, normalized to $T = 20°$C

Leakage currents

- After irradiation $\Delta I = \alpha V \phi$
- Calculate the current related damage constant α
- Use I at $V_{bias} = V_{depl.}$, normalized to $T = 20°$C
- Obtained for 24 GeV proton, $\overline{\alpha} = 2.78 \times 10^{-17}$ A/cm

Leakage currents

- After irradiation $\Delta I = \alpha V \phi$
- Calculate the current related damage constant α
- Use I at $V_{bias} = V_{depl.}$, normalized to $T = 20°$C
- Obtained for 24 GeV proton, $\overline{\alpha} = 2.78 \times 10^{-17}$ A/cm
- Normalizing fluence to equivalent 1 MeV n, $\rightarrow$ hardness factor $k_\alpha = 0.61$

Strip tests

- total strip capacitances
- inter-strip capacitances
- coupling capacitances

$\longrightarrow$ essentially unchanged after irradiation

Overview

- LHCb spectrometer and the Silicon Tracker
- Sensor quality assurance program and results on first sensors
- Irradiation tests with IT prototype sensors
- Summary

Summary

- LHCb Silicon Tracker uses silicon micro-strip detectors
  - $\sim 200\ \mu$m pitch
  - readout strips up to 38 cm in length

Summary

- LHCb Silicon Tracker uses silicon micro-strip detectors
  - $\sim 200\ \mu$m pitch
  - readout strips up to 38 cm in length
- Presented QA program
  - results on first sensors very satisfactory
  - low leakage currents; electrical parameters within specification

Summary

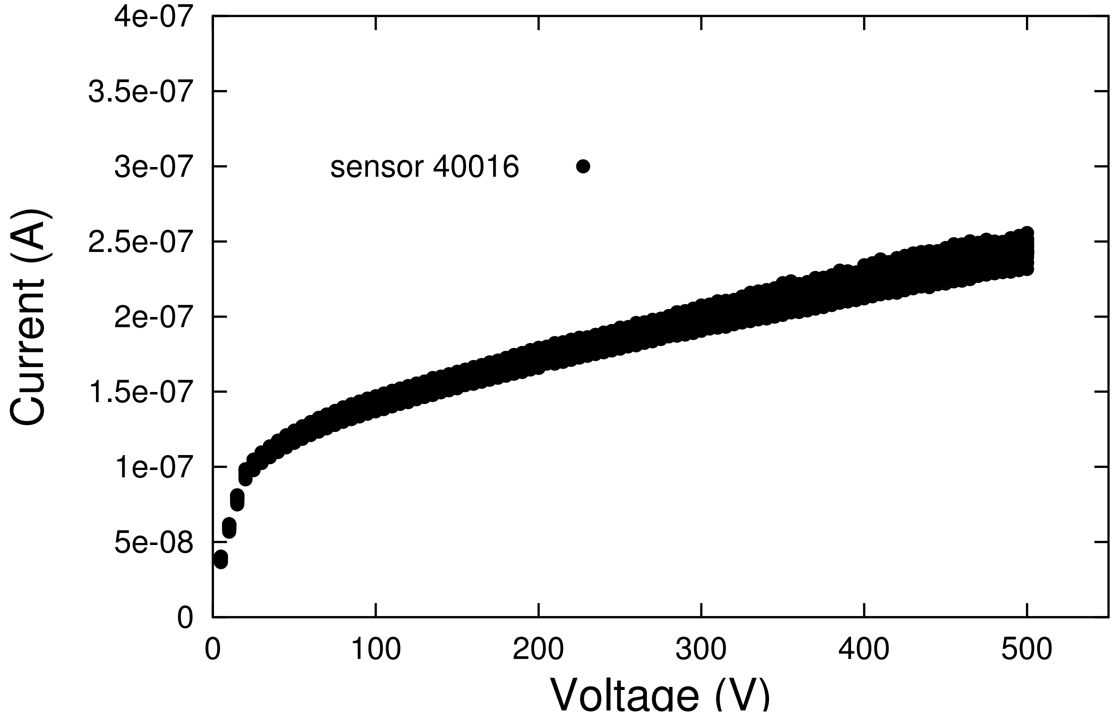
- LHCb Silicon Tracker uses silicon micro-strip detectors
  - $\sim 200\ \mu$m pitch
  - readout strips up to 38 cm in length

- Presented QA program
  - results on first sensors very satisfactory
  - low leakage currents; electrical parameters within specification

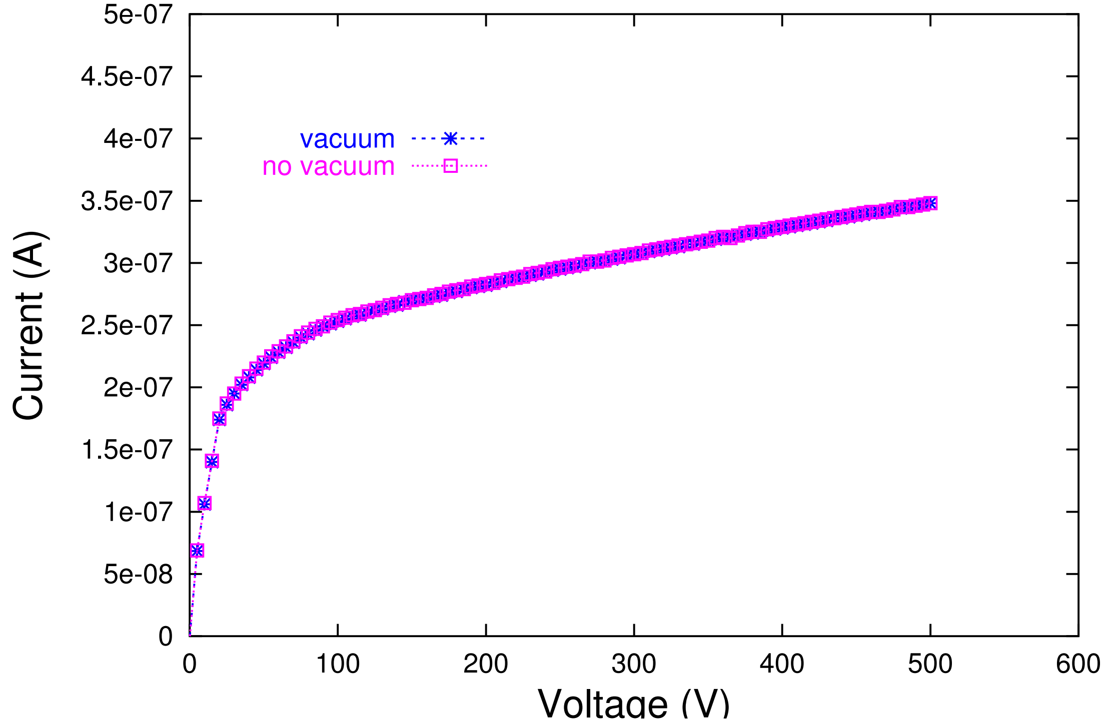
- Performed irradiation on IT prototype sensors with 24 GeV/c protons
  - depletion at 50 V after equivalent to 7 LHCb years in IT
  - current related damage constant $\alpha = 2.78 \times 10^{-17}$ A/cm, hardness factor $k_\alpha = 0.61$
  - strip capacitances, coupling capacitances: unchanged after irradiation

Back-slides

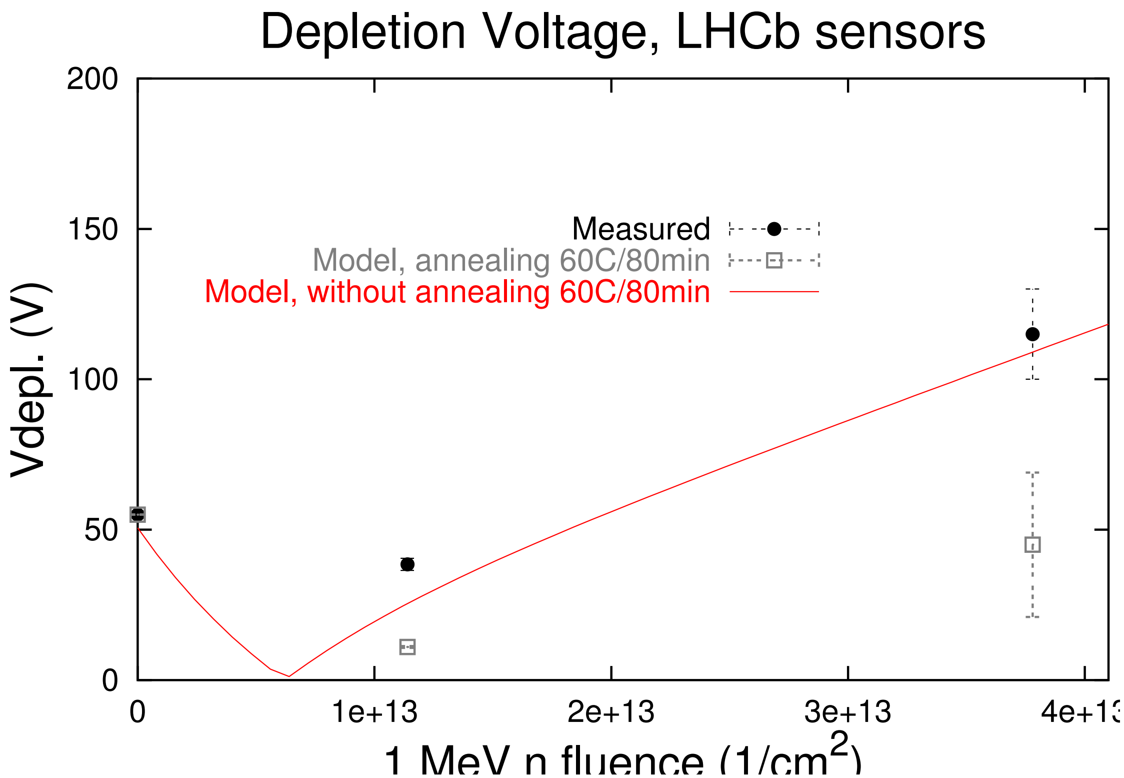
Reproducibility IV curves



No chuck vacuum effect



Depletion voltages vs. Hamburg model



I vs T

Leakage current:

$$I(T) = I(T_m)\left(\frac{T}{T_m}\right)^2 exp\left(-\frac{E_g}{2k_B}\left\{\frac{1}{T} - \frac{1}{T_m}\right\}\right)$$

- $E_g = 1.12$ eV band gap energy in silicon at room temperature
- k_B Boltzmann constant
- T and T_m in K
- relation true if current caused by generation current in the bulk material (case after irradiation)

References

- *LHCb Technical Design Report, Reoptimized Detector Design and Performance*. CERN/LHCC 2003-030.
- *LHCb Inner Tracker Technical Design Report*. CERN/LHCC 2002-029.
- O. Steinkamp. *Silicon strip detectors for the LHCb experiment*. Nucl. Instr. and Meth. A 541 (2005) 83.
- F. Lehner, C. Lois and H. Voss. *Measurements on irradiated silicon sensor prototypes for the Inner Tracker of LHCb*. LHCb note 2004-104.
- G. Baumann et al., *Pre-series Sensor Qualification for the Inner Tracker of LHCb*. LHCb note in preparation.

Table of Contents