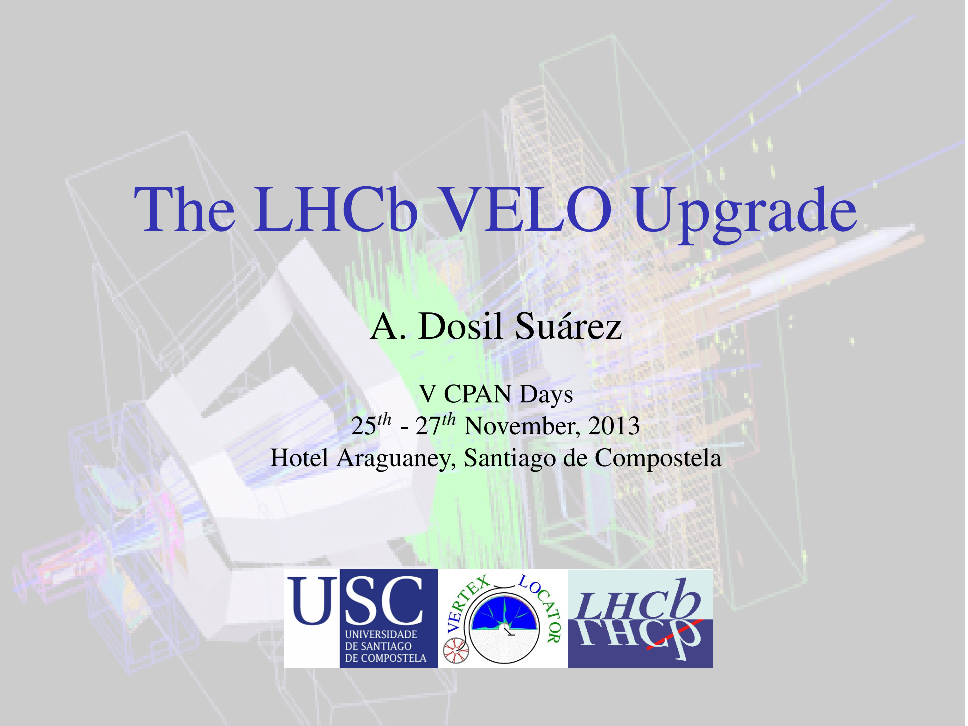


The LHCb VELO Upgrade

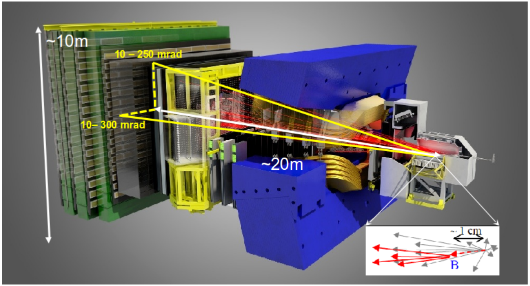
A. Dosil Suárez

V CPAN Days
25th - 27th November, 2013
Hotel Araguaney, Santiago de Compostela

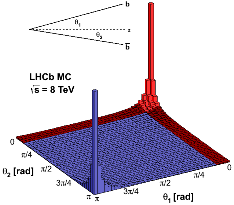
Outline

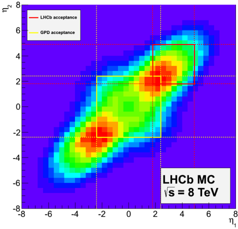
The LHCb experiment

LHCb is a forward spectrometer designed to study flavor physics exploiting the enormous production cross sections of heavy hadrons at the LHC

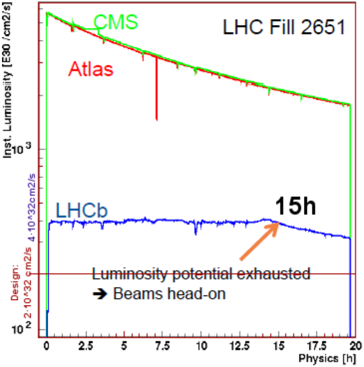


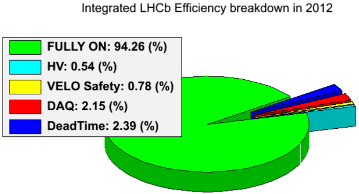
- Excellent vertex, momentum and particle identification
- $2 < \eta < 5$
- 40% of heavy quark production x-section within 4% of solid angle





The LHCb experiment

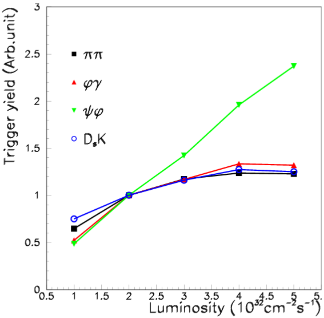




- Design luminosity lower than the LHC can deliver.
  - → Built for $\mathcal{L} = 2 \times 10^{32} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ at 25 ns spacing, with an average of μ=0.4 interactions per bunch crossing
  - → Running at a $\mathcal{L} = 4 \times 10^{32} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ at 50 ns spacing with μ=1.4
  - → Has recorded 1.1 fb^{-1} in 2011 and 2 fb^{-1} in 2012
- Almost all LHCb results are completely dominated by statistical uncertainties $\Rightarrow$ Need more statistics!
- At long shutdown 2 (2018) we hope to have $\sim$3x the current statistics
  - → All detectors with $>\sim 99\%$ active channels
  - → ϵ(operation)>94%
  - → $\sim$98% are good data
- Another factor 2 in statistics will take 5 years more

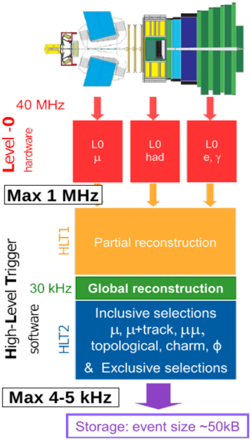
Current LHCb limitations

- Main limitation is the 1 MHz readout of front-end electronics
- First level (L0) trigger based on calorimeter and muon systems
- Keeping < 1 MHz triggers at higher lumi means increasing thresholds
- Saturation of trigger yield in hadronic final states at $\mathcal{L} = 4 \times 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- In addition the current detector not designed for higher lumi → faster aging

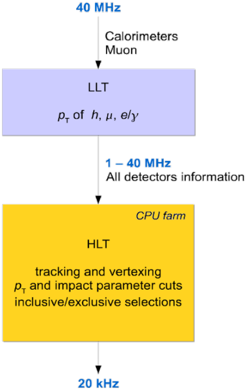


LHCb upgrade

Current data flow



Upgraded data flow


40 MHz

Calorimeters
Muon

LLT

p_T of h, μ, e/γ

1 – 40 MHz
All detectors information

CPU farm

HLT

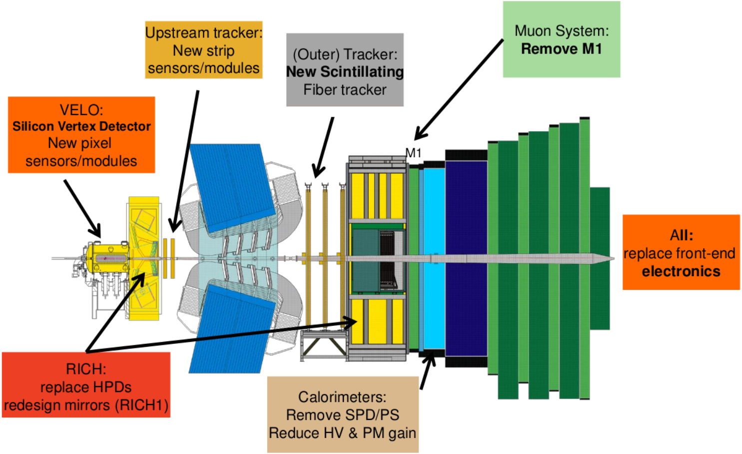
tracking and vertexing
p_T and impact parameter cuts
inclusive/exclusive selections

20 kHz

- Remove Hardware trigger. Use software-only trigger
- 1 to 40 MHz trigger rate
- Output rate from 5 to 20 kHz
- Increase luminosity to $\geq 2 \times 10^{33}$ cm^{-2}s^{-1}
- We aim to record 10 fb^{-1} per year

Apart from the increase in luminosity and trigger rate, we expect an increment of a factor 10 and 20 in the muonic and hadronic channels yield respectively.

Detectors upgrade



Upstream tracker:
New strip
sensors/modules

(Outer) Tracker:
New Scintillating
Fiber tracker

Muon System:
Remove M1

VELO:
Silicon Vertex Detector
New pixel
sensors/modules

All:
replace front-end
electronics

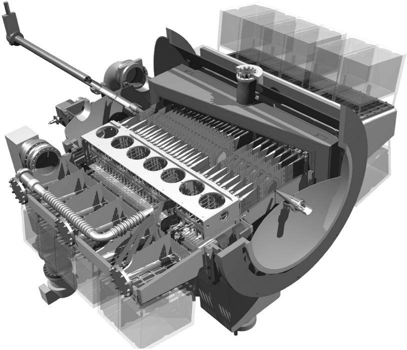
RICH:
replace HPDs
redesign mirrors (RICH1)

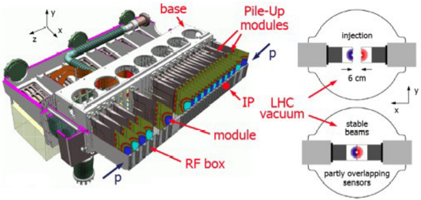
Calorimeters:
Remove SPD/PS
Reduce HV & PM gain

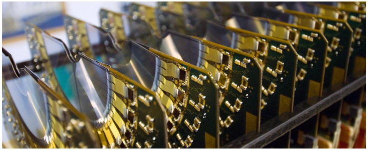
See Cristina Fernández Bedoya's talk: *Upgrade plans for LHC detectors*

The Vertex Locator (VELO)

- Silicon strip detector surrounding the interaction point
- 88 silicon n$^+$-on-n sensors, 300 μm thick, R-ϕ design
- Located only 8 mm from the beams
- Enclosed into a separated vacuum box (RF Foil)
- Halves are separated for beams injection
- 1 MHz trigger rate
- Bi-phase CO_2 cooling system



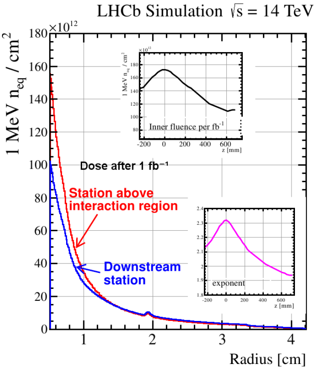


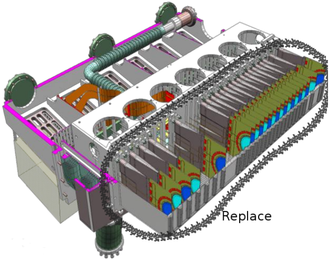


VELO upgrade

Requirements and challenges

- Data-driven readout at 40 MHz ⇒ up to 2.85 Tbit/s from whole VELO
- Radiation tolerance. Highly non-uniform radiation: $5.2 \times r^{-1.9}$ hits $\text{event}^{-1}\text{cm}^{-2}$
- Keep/improve performance
- Increase granularity to allow operation at $\mathcal{L} \geq 2 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$



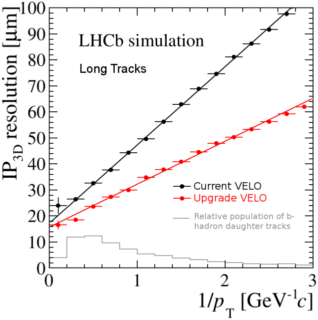


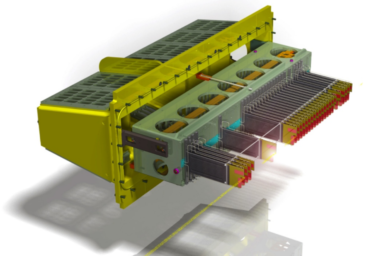
- Sensors, electronics, modules and RF foil need to be replaced
- Vacuum tank, cooling plant and motion system will be re-used

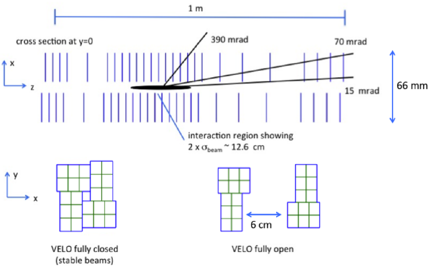
VELO upgrade

Characteristics of the new VELO

- From micro-strips to pixels
- Full detector consists of 26 stations
- 1 station = 2 modules, one on either side of the beam
- Closest pixel is at 5.1 mm from the beam centre
- Geometrical efficiency > 99 % for R < 10 mm
- Track rate (and radiation damage) will be 10x higher

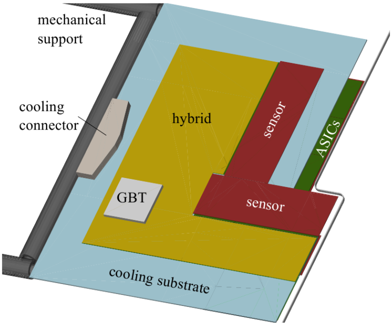




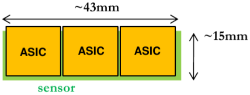


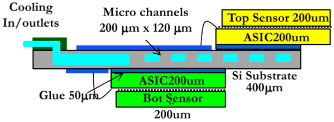
Modules

- 4 sensor tiles, 2 on each side of substrate
- Each tile contains 3 ASIC chips for readout
- Silicon substrate with integrated micro-channels for cooling
- Material in active region ∼0.9% X0



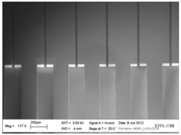
- based on Velopix ASIC (successor of Timepix3) 55 μm x 55 μm pixel size, 256 x 256 matrix
  - → simultaneous measurement of time-over-threshold (ToT) and time-of-arrival (ToA)
  - → peaking time < 25 ns, timewalk < 25 ns
  - → hit rate up to 900 MHits/s. (Above 15.1 Gbit/s)
  - → Data driven readout: each hit is time-stamped, labeled and sent off chip immediately
  - → submission planned for 2014 Q3

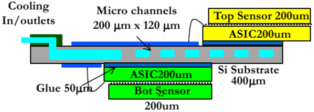


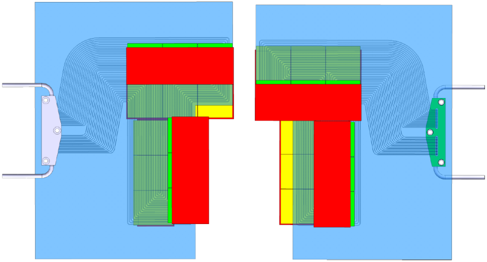


Cooling

- High speed pixel readout chips produce a lot of heat ($\sim$1.5 W/cm^2)
- Keep the sensors at $<$ -20°C to minimize the effects of radiation damage, and to avoid thermal runaway
- Novel method: evaporate CO_2 via micro-channels etched in Si substrate
- Bring the cooling power where you need it, using least material
- No CTE difference (Si on Si)

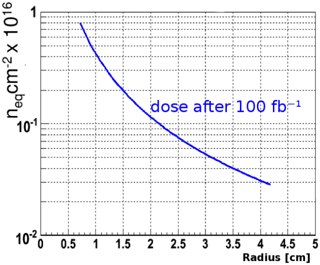


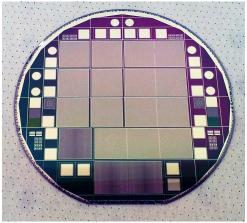




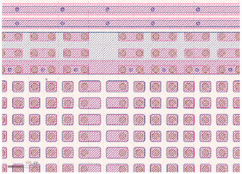
Silicon sensors

- Planar silicon, n-in-n or n-in-p to be decided
- Tile for 3 VeloPix chips: ∼43 x 14 mm, thickness 200 μm
- 55 μm x 55 μm pixel size
- Non homogeneous irradiation sets constraints on guard ring design
  - → factor ∼40 difference in fluence from tip to far corner
  - → bias voltage at end on life ∼1000 Volts for tip
  - → guard ring width ∼400 μm

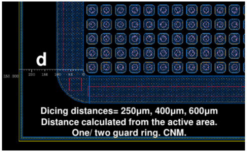




Sensor wafer with variable guard ring designs
(Tiles 2-1 and 3-1. CNM, USC)



Sensor layout of inter-chip areas. Micron

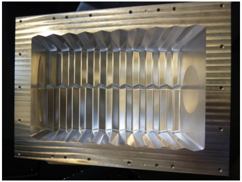


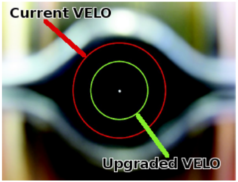
RF foil

The RF foil is a *de facto* beam pipe

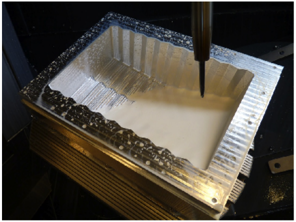
Severe requirements:

- Vacuum tight ($< 10^{-9}$ mbar l/s)
- Radiation hard
- Low mass but rigid to prevent deflection onto the sensors or pinhole leaks
- Good electrical conductivity to mirror beam currents and shield against RF noise pick-up in FE electronics
- Thermally stable and conductive (heat load from the beam)





Material and fabrication:

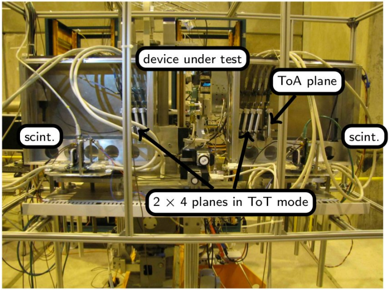


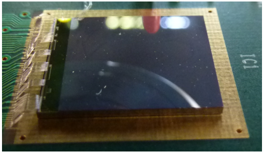
- Mill foil from solid Al alloy block
- By 5-axis milling head
- Achieve 300 μm thickness
- More flexibility to change shape than the pressing method
- Chemical etching to reduce 100 μm more

Test beam

TimePix telescope

- Constructed for LHCb upgrade
- Timepix assemblies (with 300 μm sensors) used as telescope planes (8 ToT + 1 ToA)
- device under test can be moved/rotated and cooled (portable CO_2 cooling plant)
- Resolution at the DUT plane $\leq 2\mu$m (with 180 GeV/c π beam)
- Track time-stamping with
  - $\rightarrow$ $\approx$ 1 ns resolution
  - $\rightarrow$ $\approx$ 3-12 kHz track rate
- available to external users within the framework of EU project AIDA WP 9.3 (USC member)



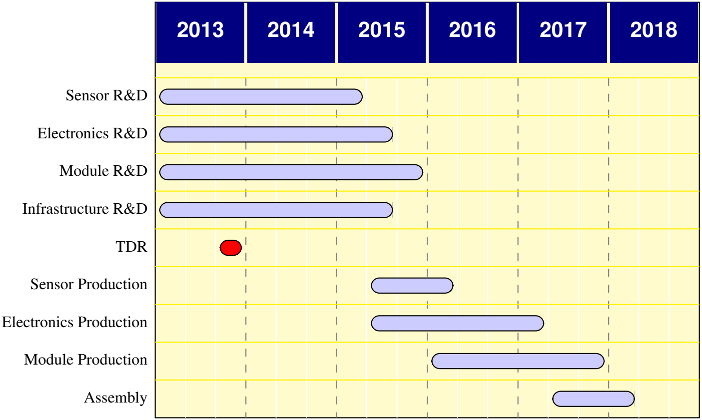


Focus on

- sensor performance after irradiation (Medipix3/Timepix3 assemblies)
- evaluation of guard-ring designs, edge efficiencies

Schedule

LoI: CERN-LHCC-2011-001
FTDR: CERN-LHCC-2012-007



... to be installed in LHC Long Shutdown 2, in 2018-2019

Conclusions

The requirements for the LHCb VELO upgrade are very demanding:

- Luminosity will be increased by a factor ≥ 10
- Trigger readout will be increased by a factor of 40
- Keep or improve the performance of the current VELO

Upgrade VELO characteristics:

- Vertex Locator will consist of planar silicon pixels, 55 x 55 μm^2
- Evaporative CO2 cooling in Silicon micro-channel substrate
- Material budget reduction in elements placed in the acceptance (modules, RF-Foil)

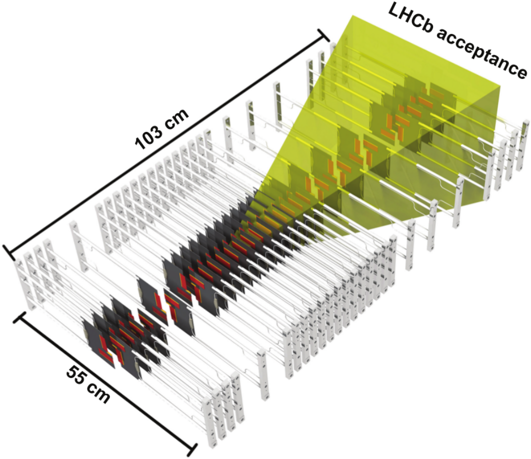
Still a lot of work to do:

- Intense testbeam program to validate: sensor technologies, radiation hardness, cooling schemes and readout electronics
- Sensor, electronics, modules and mechanics production

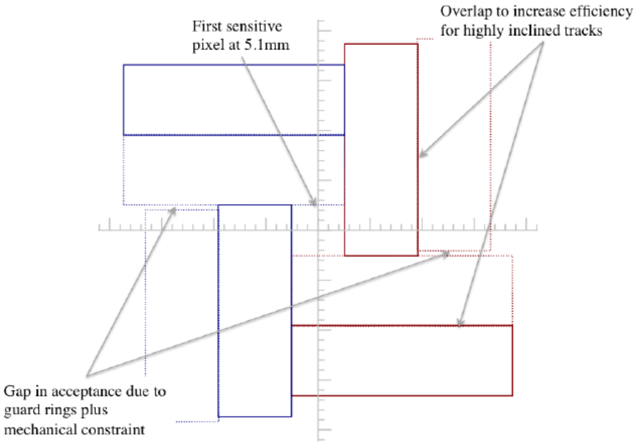
Installation during long shutdown 2 in 2018

Backup

Backup

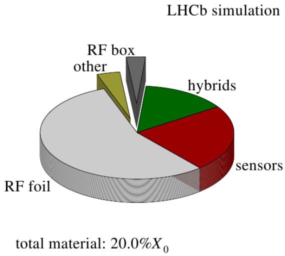


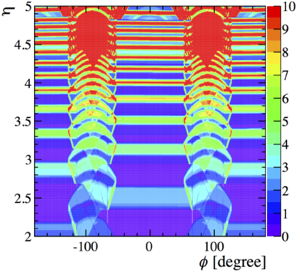
Backup



First sensitive pixel at 5.1mm
Overlap to increase efficiency for highly inclined tracks
Gap in acceptance due to guard rings plus mechanical constraint

Backup


LHCb simulation
RF box
other
hybrids
sensors
RF foil
total material: 20.0%X_0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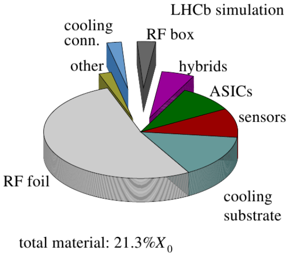
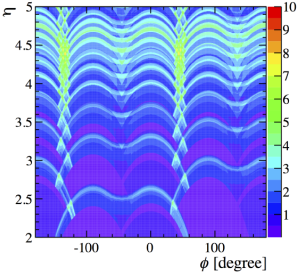

LHCb simulation
cooling conn.
RF box
other
hybrids
ASICs
sensors
RF foil
cooling substrate
total material: 21.3%X_0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Backup

$$\sigma_{\mathrm{IP}}^2 = \frac{r_1^2}{p_{\mathrm{T}}^2\sqrt{2}}\left(0.0136\sqrt{\frac{x}{X_0}}\left(1+0.038\ \ln\left(\frac{x}{X_0}\right)\right)\right)^2 + \frac{\Delta_{02}^2\sigma_1^2+\Delta_{01}^2\sigma_2^2}{\Delta_{12}^2}$$

Comparison between current and upgraded VELO

- A smaller RF foil inner radius (3.5 versus 5.5 mm)
- A smaller inner edge distance to the beams for the sensitive part; $R_{det} \sim 5.1$ mm(square hole) versus 8 mm (round hole)
- A coarser inner pitch (p = 55 μm pixels versus 40 μm strips)
- A smaller Si thickness ($t_{det} + t_{ASIC} = 0.4$ versus $t_{det} = 0.6$ mm for an R-*phi* station)
- A smaller z distance between stations ($\Delta z = 25$ versus 30 mm).