The LHCb VELO upgrade

a perspective from Manchester

Pablo Rodríguez on behalf of the LHCb Manchester group.

The University of Manchester

Outline

LHCb VELO upgrade

- Current LHCb VELO.
- Motivation for the upgrade.
- Implications:
  - Module.
  - Cooling.
  - Sensors and ASIC.

Manchester's responsibilities

- Tasks.
- Equipment.
- Assembly.
- Glue studies.
- Thermal studies.
- Readout.
- Simulations.

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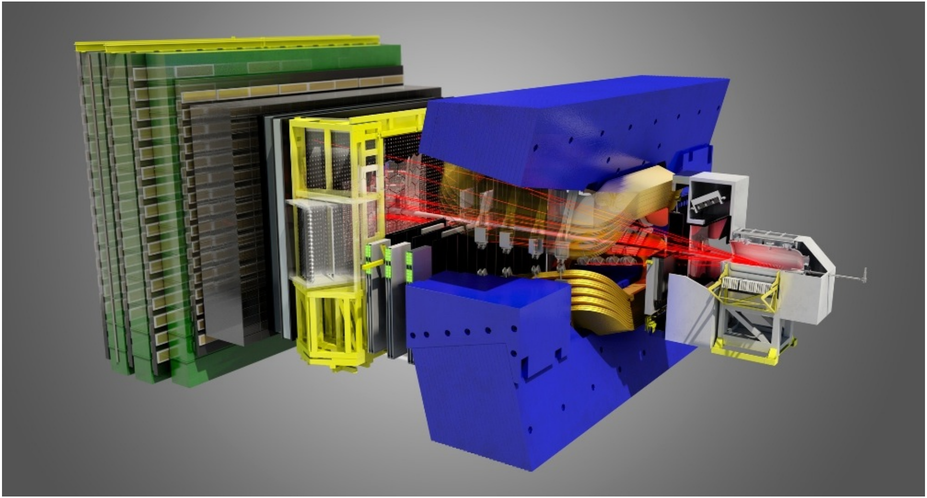
The aim of the LHCb experiment is to search for New Physics beyond the SM by studying CP Violation and rare decays of beauty and charm particles at the LHC.



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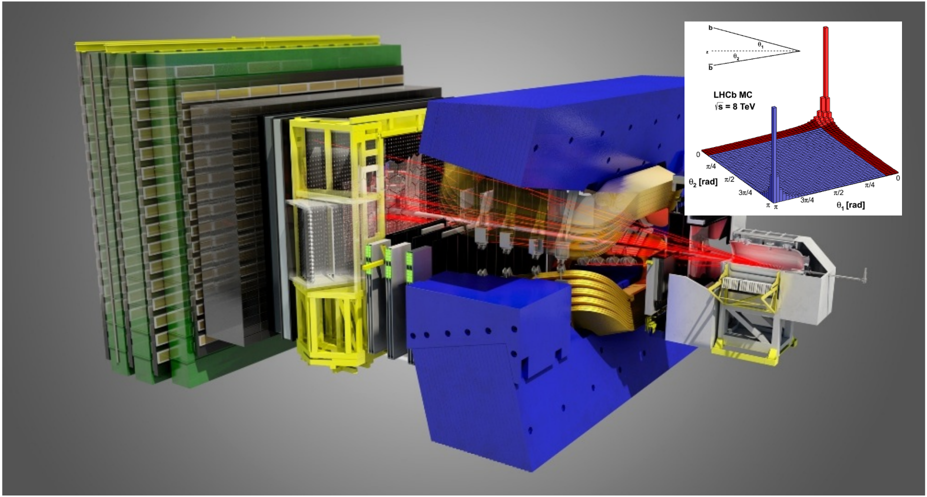

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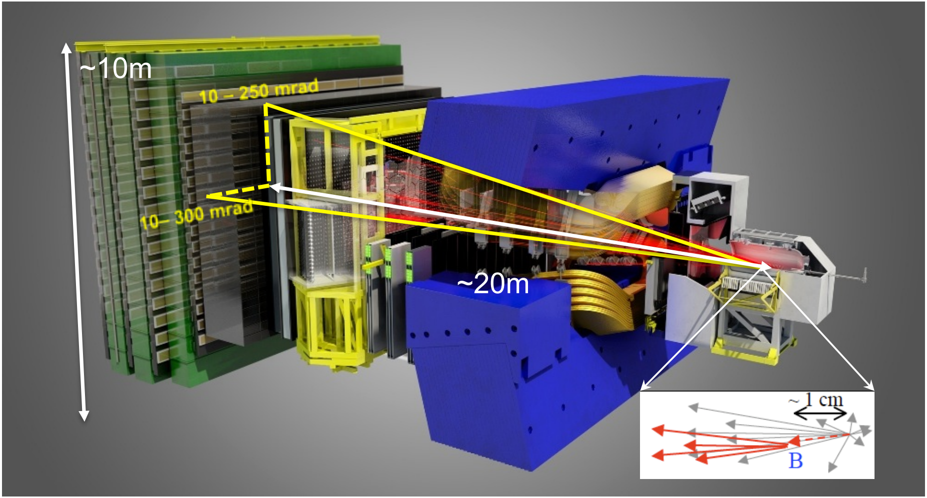

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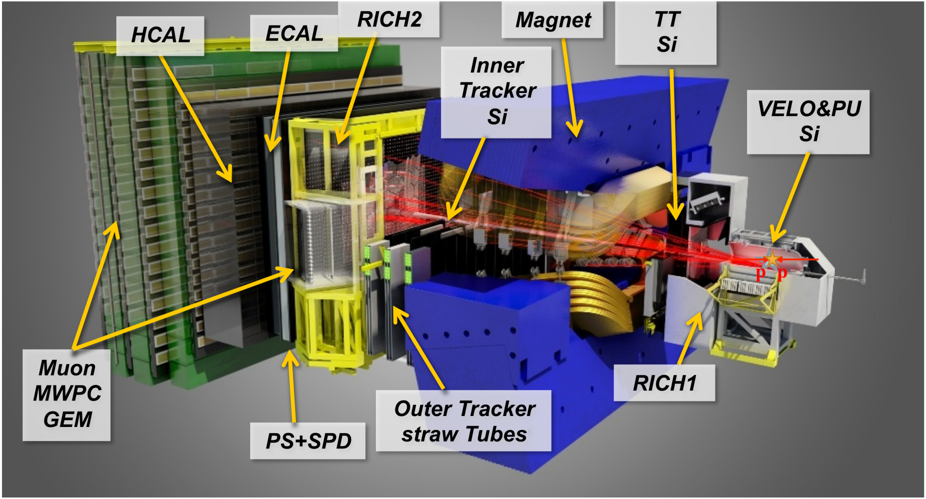

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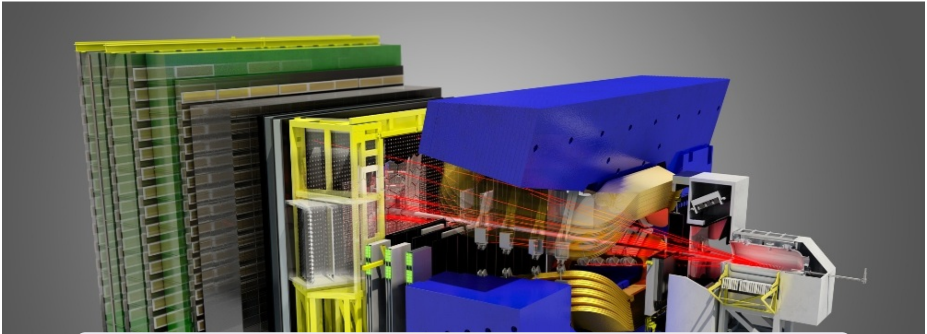
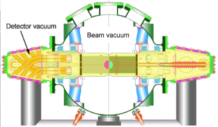
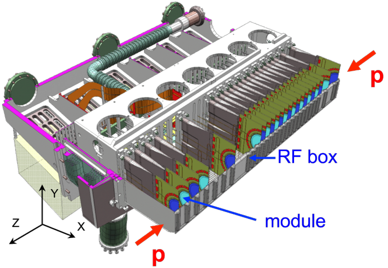
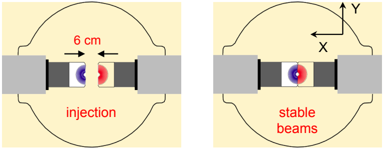


- Dedicated Trigger system for B and C mesons.
- Great Vertex Resolution! Primary/secondary separation, proper time resolution.
- Excellent momentum and mass resolution.
- Outstanding PID and μ reconstruction.

The current VELO

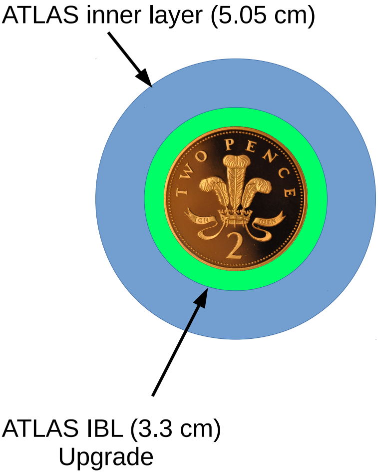


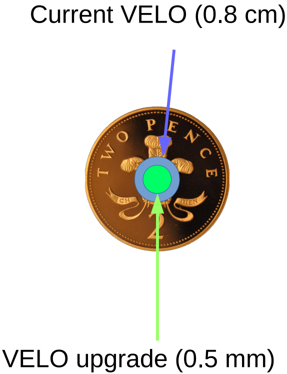




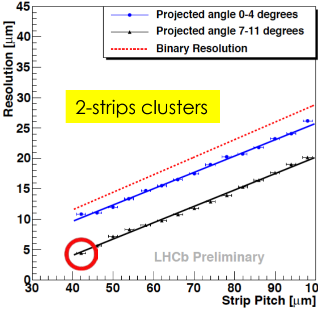
- Operates in the secondary vacuum.
- Separated from the LHC vacuum by a 300 μm RF foil.
- 2 retractable detector halves at 5.5 (29) mm from the LHC beams when closed (open).
- 21 modules per half with R and ϕ micro-strip sensors:
  - 300 μm n$^+$-on-n sensors (one module n$^+$-on-p).
  - R sensors pitch: 40-101.6 μm.
  - ϕ sensors pitch: 35.5-96.6 μm .
- CO_2 bi-phase cooling system (plant: -30°C, sensors: -10°C).
- First active strip @ r $\approx$ 8.2 mm.

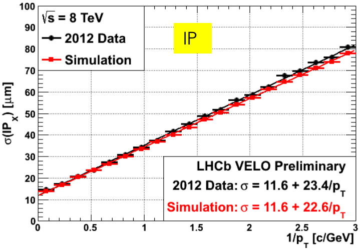
Inner radius

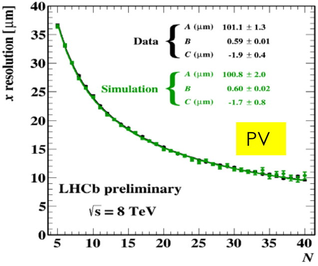




Performance







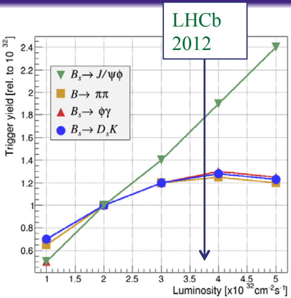
Resolution

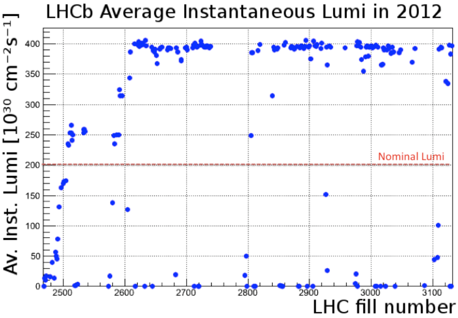
- Excellent spatial resolution (4 μm).
- $\sigma_{\rm IP} = 11.6 + 23.4/p_{\rm T}\ \mu$m.
- PV resolution of $\sigma_{\rm x,y} = 13\ \mu$m and $\sigma_{\rm z} = 69\ \mu$m for 25 tracks.

LHCb upgrade: motivation

Current LHCb

- Current LHCb is running above design parameters (1-2 fb^{-1}/year) but:
  - many physics channels will still be statistically limited by 2018.
  - LHC can deliver even more.
- Signal yield do not scale with luminosity:
  - in particular not for hadronic final states.
  - L0 hardware limitations.





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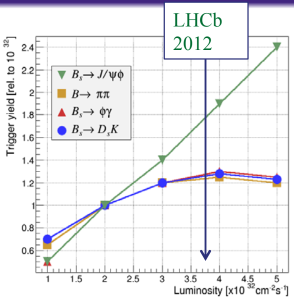
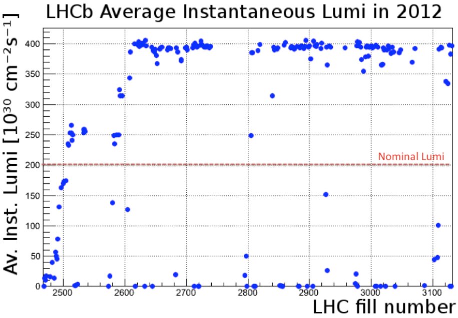




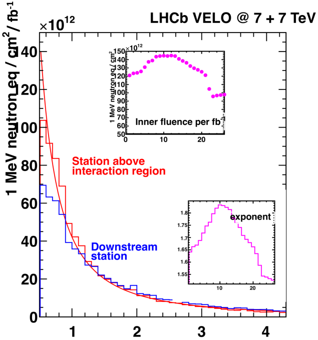
Upgrade strategy

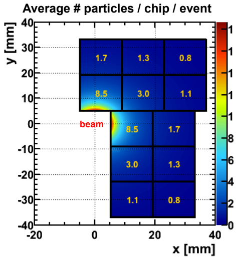
- Read out the full detector at 40 MHz rate.
- Trigger implemented fully in S/W.
- This will allow to operate the detector at $\mathcal{L} \geq 2 \times 10^{33}$ cm^{-2}s^{-1}.
- Requires replacement of front-end electronics.

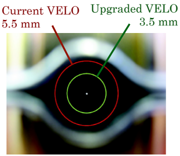
Implications for the VELO upgrade

Higher luminosity

- Withstand radiation levels up to 8×10^{15} $1\text{MeV}\text{n}_{\text{eq}}\text{cm}^{-2}$
- Highly non-uniform occupancy.
- Highly non-uniform cooling/HV requirements.
- Closer to beam:
  - RF foil: from 5.5 to 3.5 mm.
  - Active region: from 8.2 to 5.1 mm.
- Better granularity needed.







Triggerless system

- Bandwidth increased by a factor of 40.
- $\sim$ 26 tracks per sensor per bunch crossing (each 25 ns).
- More than **2 Tbit/s** from whole VELO.

The VELO upgrade plan

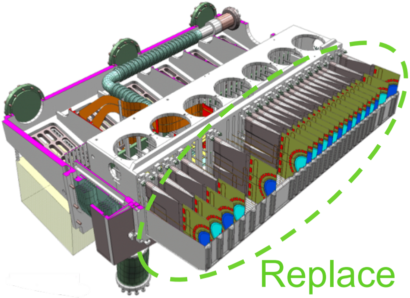
Refurbished systems

- CO_2 cooling plant.
- LV & HV power supply systems.
- Vacuum vessel and equipment.
- Motion system.

New components

- Detector modules based on pixel sensors.
- New ASIC (VeloPix).
- Enhance module cooling interface.
- New design of low material RF foil between beam and detector vacuum.
- Multi Gb/s readout system.

[1]



[1] *The LHCb VELO Upgrade*, NIMA. ISSN 0168-9002, April 2013.

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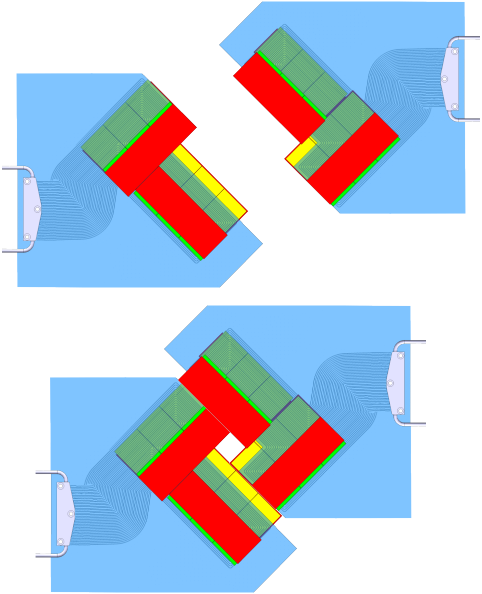


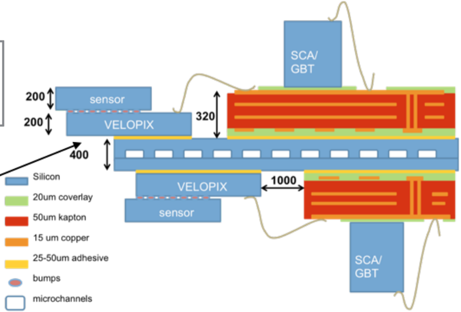
1

Microchannel cooling

In the current VELO we loss more than 7 degrees in transfer heat.
In the VELO upgrade the heat source is under the sensors.

Circulate the CO_2 at high pressure in a secondary vacuum environment.
No leaks are tolerated!

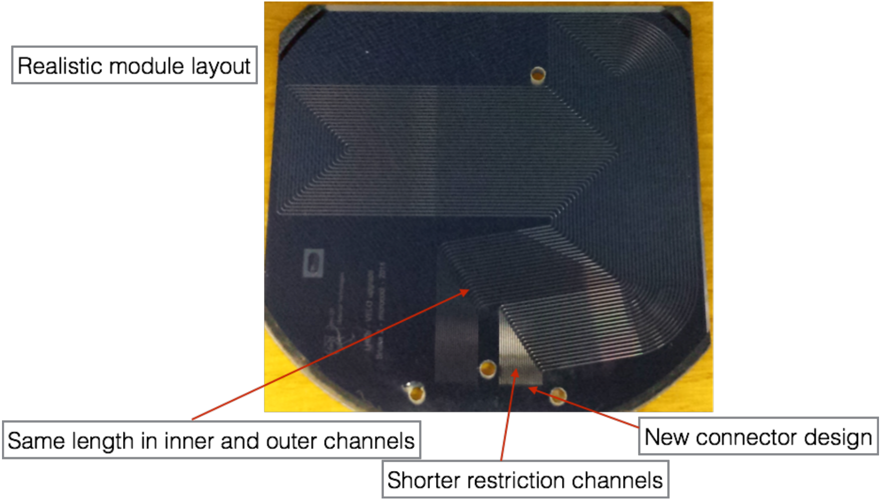
Sensor tip is overhanging by 5 mm:
$\Delta T < 8°C$ (always $T<-20°C$).



- Pressure at operational temperature ~ 20-30 bar.
- Pressure at room temperature ~ 60 bar.
- For safety, μ-channels must hold 150 bar.

Microchannel cooling

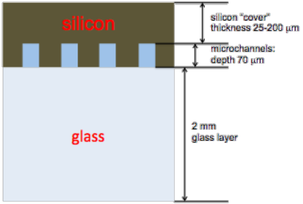
In the current VELO we loss more than 7 degrees in transfer heat.
In the VELO upgrade the heat source is <u>under the sensors</u>.

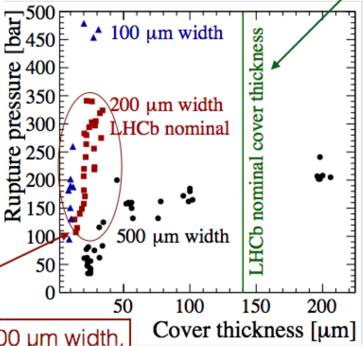


Microchannel cooling

Si-Pyrex® samples with 3 micro-channel widths, and different cover thickness were tested.

140 μm is a "safe" cover thickness to withstand mechanical requirements.

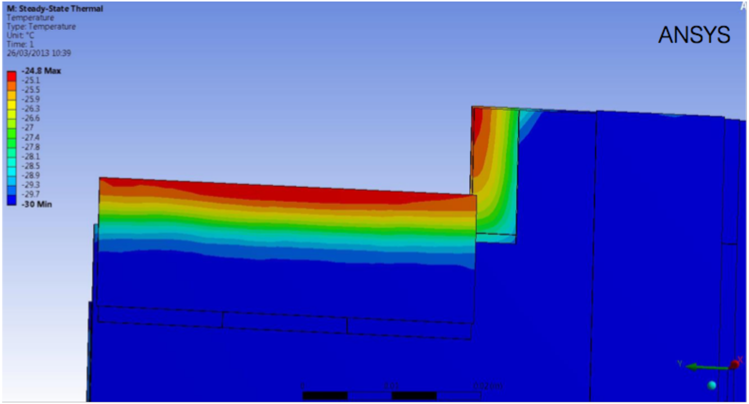




Micro-channels will be etched with 200 μm width.

In terms of pressure, we are safe. 😄

Microchannel cooling



Simulation conditions:

- Source of heat: 3 W/ASIC
- CO_2 at -30°C.
- ASIC to substrate: 100 μm Stycast® 8550FT + catalyst 9 (1.25 W/mK).

$\Delta T_{sim} \lesssim$ 7.4°C between the tip of the sensors and the micro channel.

Microchannel cooling

Change of inlet and outlet:

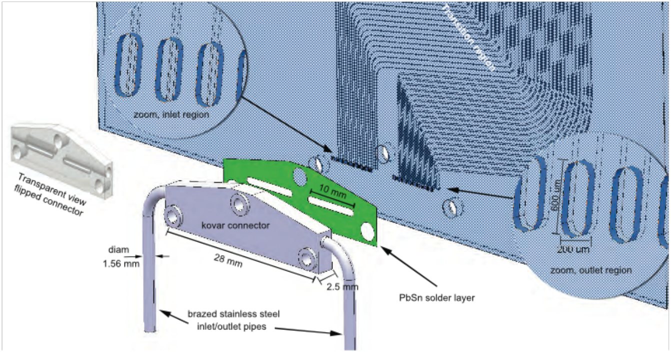
- ‘slits’ 200μm x10 mm instead of 500μm diameter holes.
  - Less pressure drop (surface increase by factor 10)
  - More pressure safety: critical dimension 200 μm instead of 500 μm.

Soldering with eutectic Pb/Sn:

- Pull test > 580 N.
- No leaks at 400 bar.

Under study:

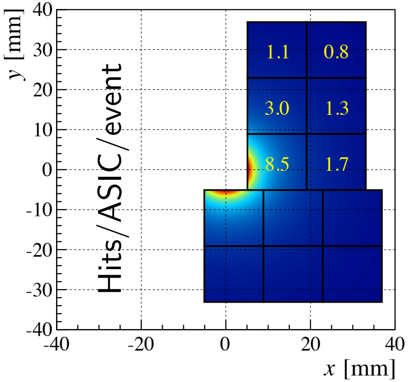
- Creep effect over time.
- Resistance to cyclic stress.



Silicon sensors

Pixel sensors

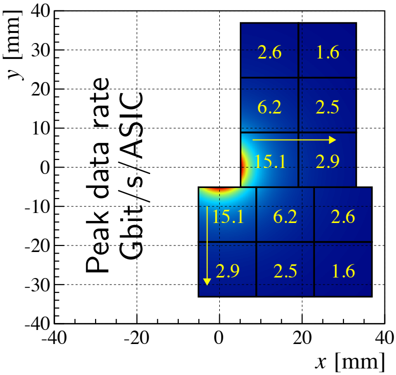
- Planar silicon sensors.
- 1000 V bias needed after 50 fb^{-1}.
- Non-uniform radiation dose:
  - From 0.8×10^{15} to 2×10^{14} n_{eq}/cm^2.
  - Factor 40 across the same sensor 0.
  - Less irradiated areas cant breakdown.
- Sensors need to withstand voltage without sparking.
- Guard ring design critical (450 μm).
- Prototyping in progress (June 2015).



ASIC and data rate

VeloPix

- Member of the MediPix family (evolution from TimePix3).
- 256 × 256 pixels, 55 × 55 μm^2 each.
- Must survive ≈ 400 MRad.
- Binary, data-driven readout of 4 2 super-pixels, time walk < 25 ns.
- Full-scale chip production 2015.
- 4 data links/ASIC, each 5.12 Gbit/s.
  - 1 4 used due to varying occupancies.
- Peak collision rate: 40 MHz.
- Hottest ASIC: 15.1 Gbit/s.
- Total 1000 optical links ≈ 3.6 Tbits/s.



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Areas were Manchester has responsibilities

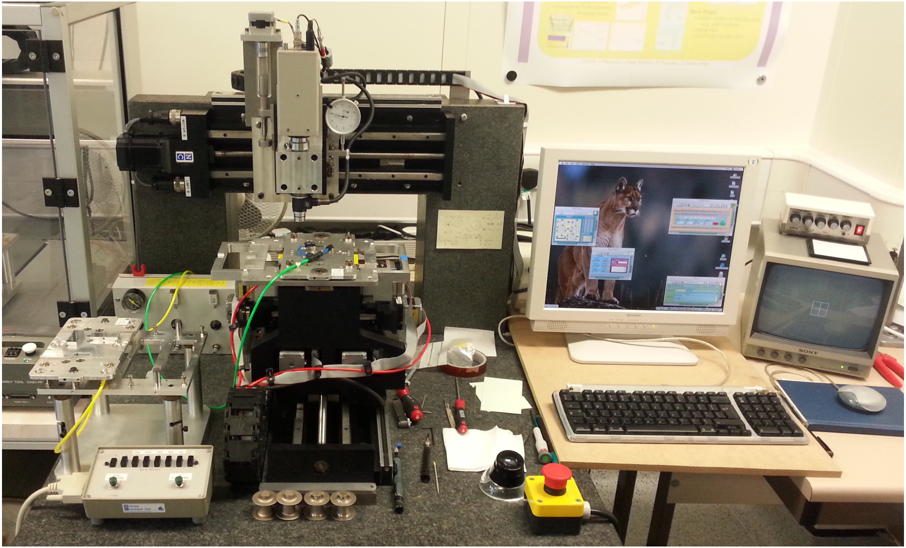
Pixel Module

- Assembly.
- Quality Assurance.
- Glue test.

Software

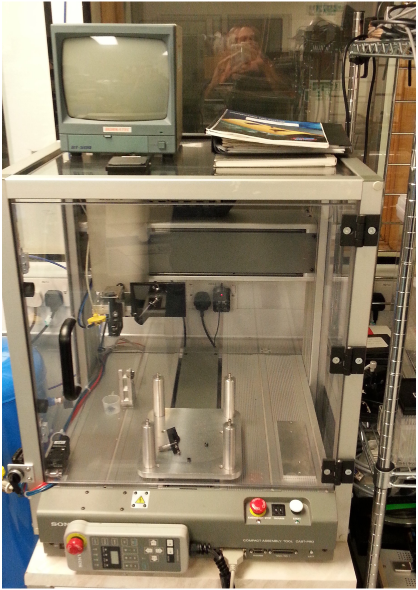
- Silicon simulations.
- Alignment.
- DAQ: FPGA and emulation.

Equipment



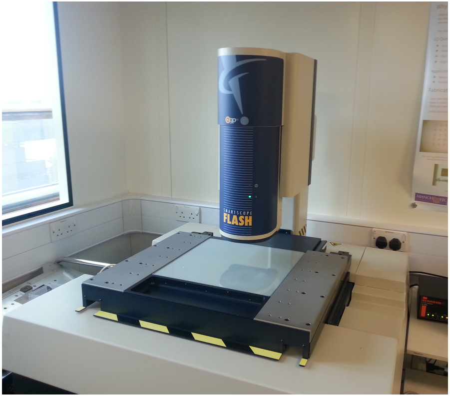
JVC video camera (custom microscope) + LabView software

Equipment



Fisnar F4200N (~5k£)

Equipment



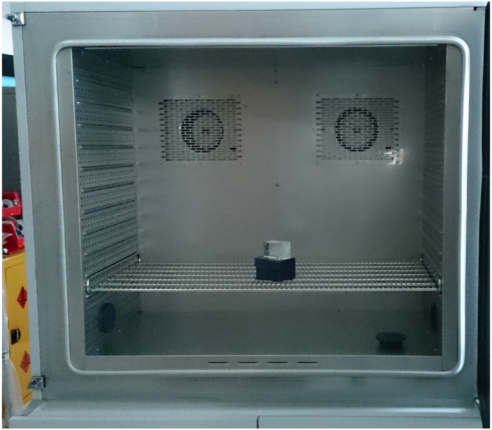
- Accuracy: 1 μm (X,Y) and 3 μm (Z)
- James Potts (master student) is practising with some silicon samples.
- Need to develop an automated procedure for metrology measurements.

Equipment

- Recently bought a F&K G5 64000
- Need to design a work-plate.
- Need to attend training course & identify the main operator.

- We expect to start practising in Spring.

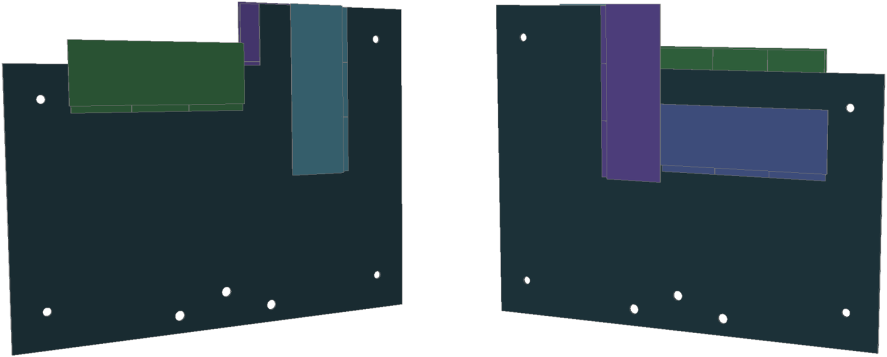
Equipment



- Climate chamber (Binder 720 MKT)
- -70 C : +180 C.

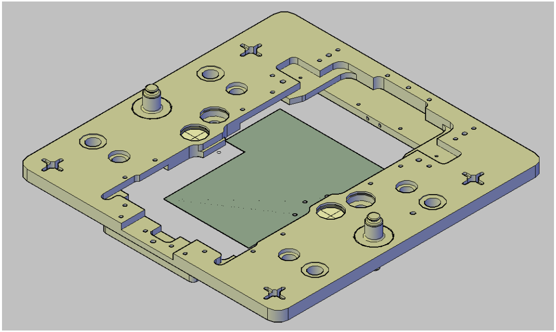
- CO2 cooling machine from RAL.

Assembly and measurement of mechanical prototype



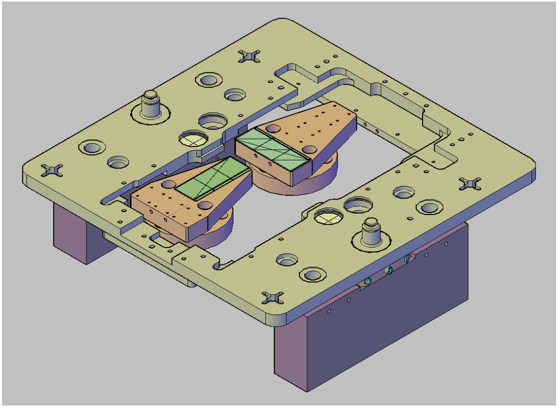
By Julian Freestone

Assembly tooling



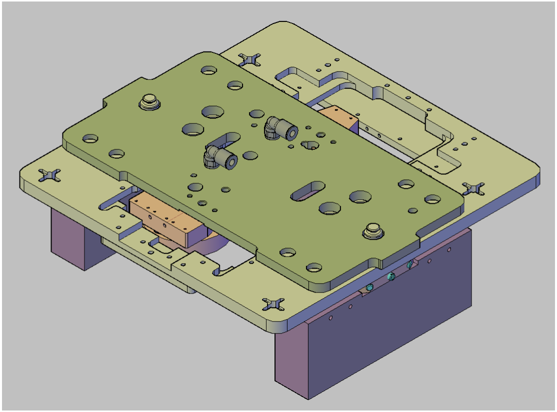
Assembly and alignment happens inside a rigid frame which has fiducials visible from both sides – the TURNPLATE

Assembly tooling



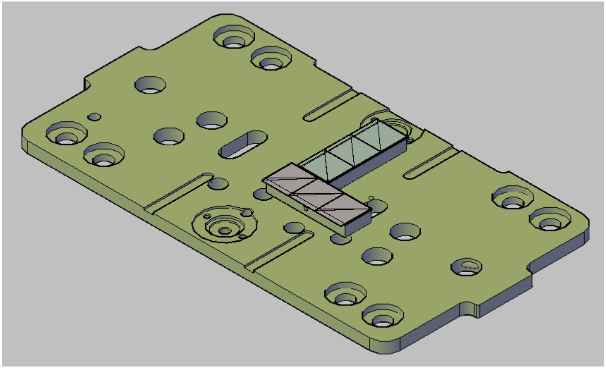
The TURNPLATE locates precisely on our positioning stage walls

Assembly tooling



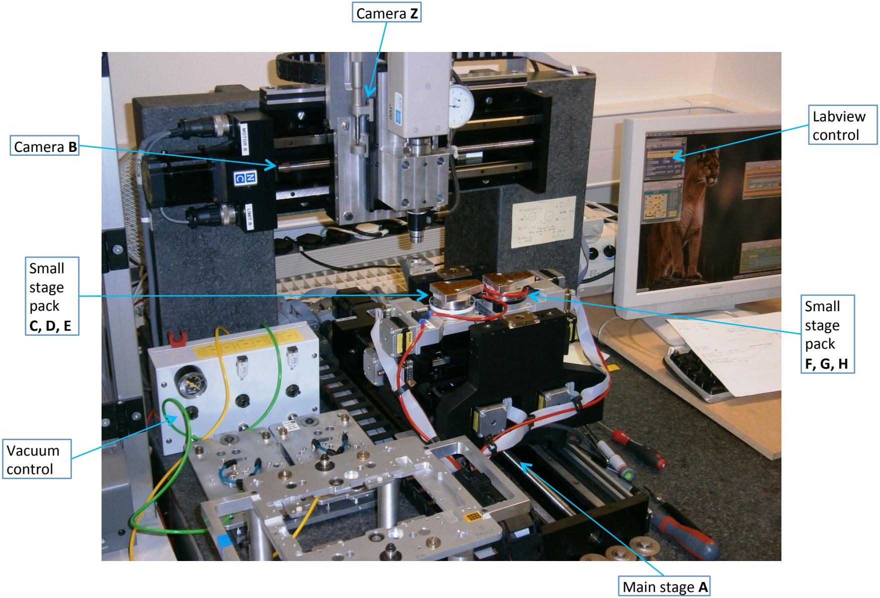
Top and bottom vacuum TRANSFER PLATES locate precisely on the TURNPLATE

Assembly tooling

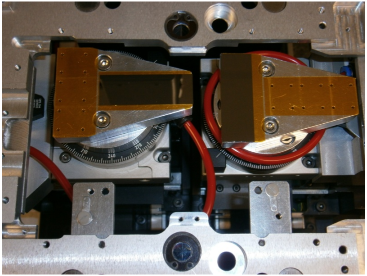


Each plate has height adjusters which allow levels to be set parallel to a reference plane and to leave a defined gap between parts for glue

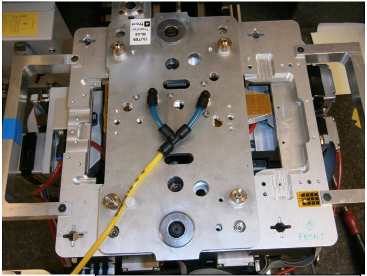
Alignment


Camera **Z**
Camera **B**
Labview control
Small stage pack **C, D, E**
Small stage pack **F, G, H**
Vacuum control
Main stage **A**

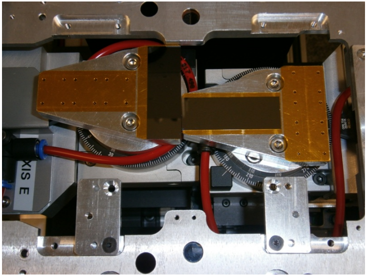
Alignment



Front pair are moved into position relative to the turnplate fiducials. Alignment errors <2µm



Transfer plate placed on top and vacuum switched to pick-up. Transfer errors <4µm

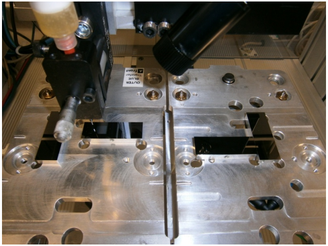


Turnplate inverted and back pair aligned

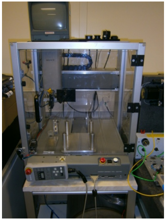
Then picked-up by the other transfer plate

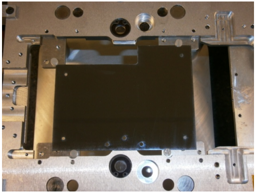
Alignment

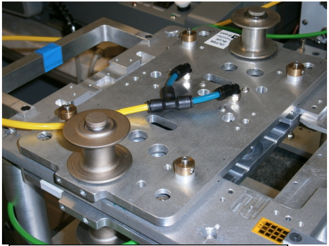
Gluing and assembly



Both transfer plates are supported on our robot platform and a pattern of glue dots applied (Araldite 2011)



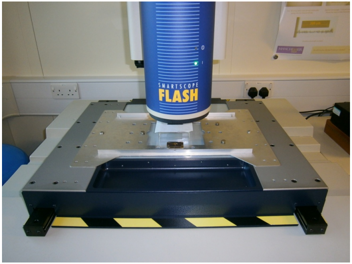


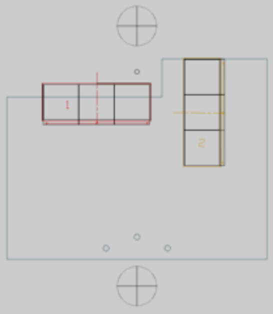


Finally all plates are brought together and held with spring clamps

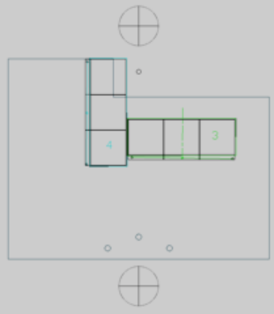
Measuring the modules with the Smartscope

The profile and fiducial positions for each 'detector' are measured with the Smartscope



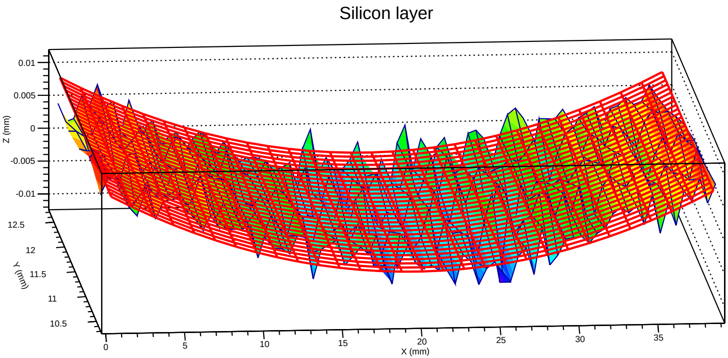


These are fitted against a CAD model and alignment parameters calculated



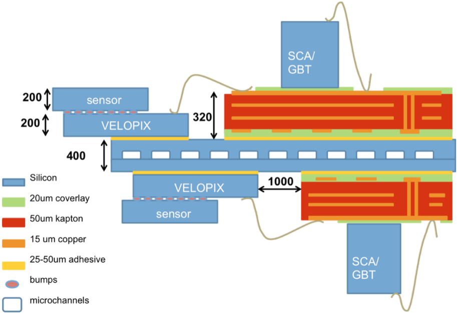
Metrology

- James Potts (MPHYS student) is working in metrology measurements with the Smartscope and analysis.
- First prototype: glass on silicon.
- Goal: create a routine which provides an accurate 3D scan of the modules.



Fitting to a 2D function: parabola in X, lineal in Y.
$z = a(x - x_0)^2 + b(y - y_0)$

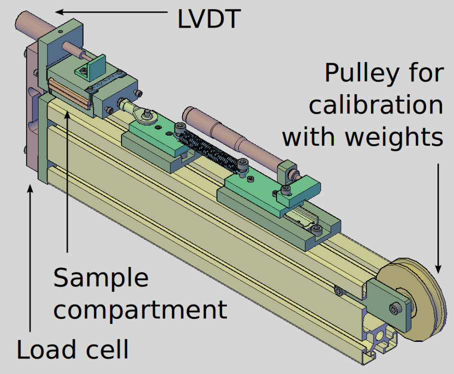
Glue studies



Motivation

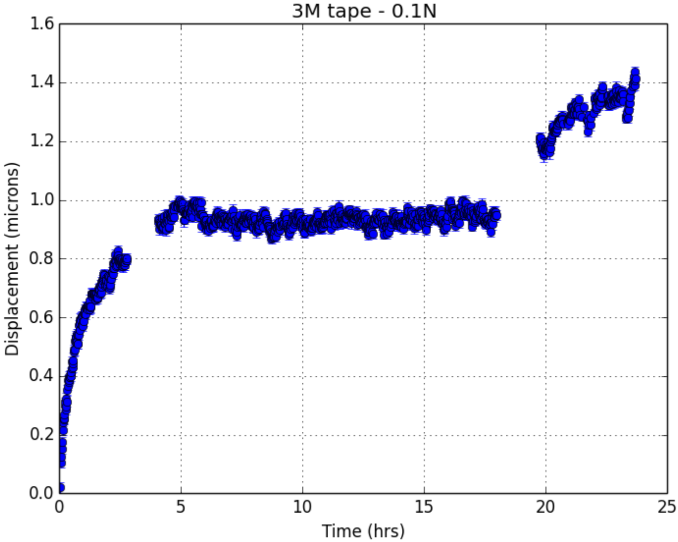
- Cooling is one of the concerns for the upgrade.
  - Glue is the interface between the hot and cold sources.
- Vertex resolution is critical for LHCb success.
  - Sensors must stay in place during 10 years.
  - Glue must survive $8 \times 10^{15}\ 1\mathrm{MeV} n_{eq} \mathrm{cm}^2$.

Glue studies: shear force test

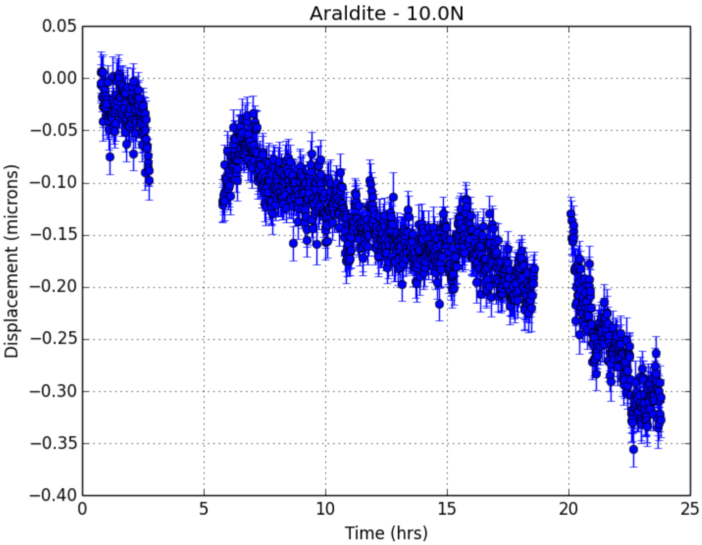


Procedure

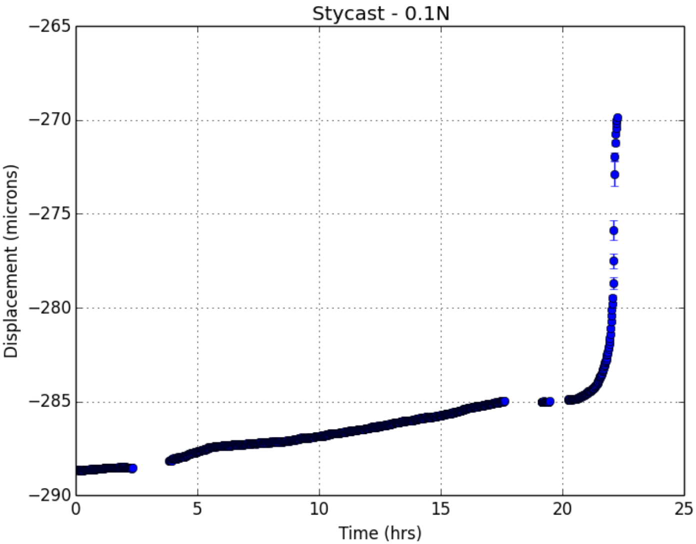
- 3 candidates: Araldite 2011, Stycast 2850 FT and 3M 9461P.
- Samples glued between aluminium plates, and thermal cycled ($-30.^{\circ}C \leftrightarrow 25^{\circ}C$).
- 15 samples irradiated up to 8×10^{15} $1MeVn_{eq}cm^{2}$.
- Long duration ($\sim$ 24 hrs) tests at weights from 0.5 N to 10 N.



By Suzanne Klaver (PhD) and Guy Stelmasiak (MPHYS).



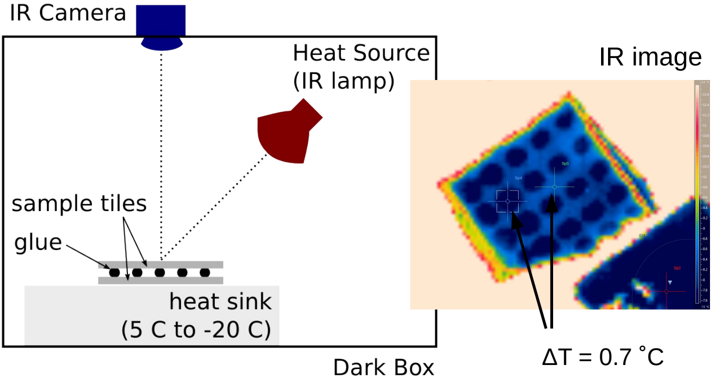
By Suzanne Klaver (PhD) and Guy Stelmasiak (MPHYS).



By Suzanne Klaver (PhD) and Guy Stelmasiak (MPHYS).

Thermal test

- Goal: cooling performance under 2 W/cm^2 and active cooling (water chiller down to -20°C).
- Samples (same as shear force test) are heated with an IR lamp.
- Temperature distribution pattern is recorded with FLIR IR camera.
- Silicon surface is coated with 3 layers of black paint to make it opaque under IR.



By Antoni Shtipliyski (MPHYS).

Thermal test

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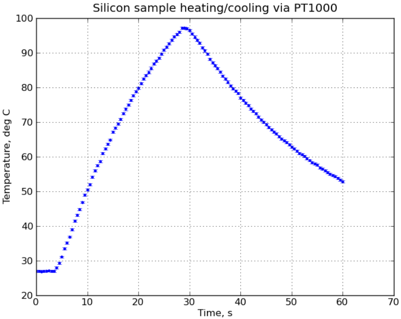
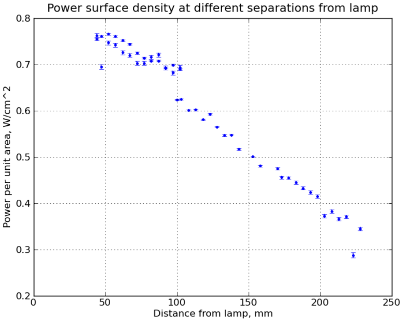
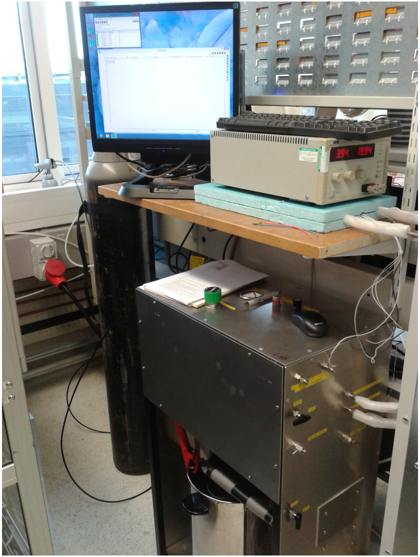
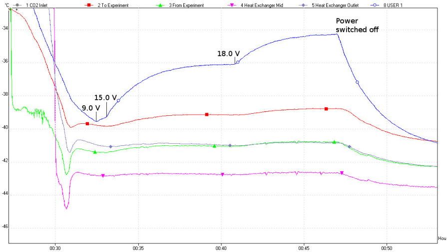




By Antoni Shtipliyski (MPHYS).

CO_2 cooling





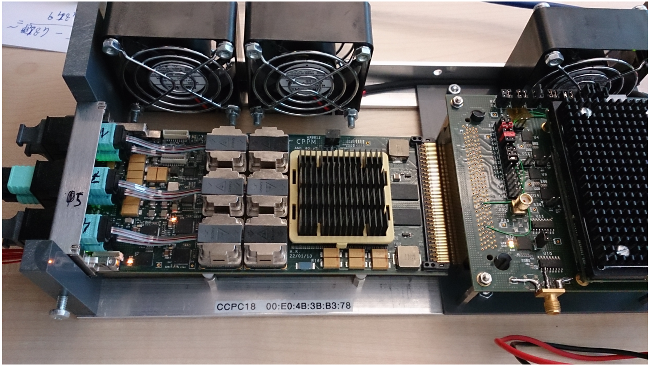
Procedure

- Study the stability and performance of a CO_2 microchannels.
- Work ongoing on a simple model (pipes).
- Microchannels should be available early next year.

DAQ

Motivation

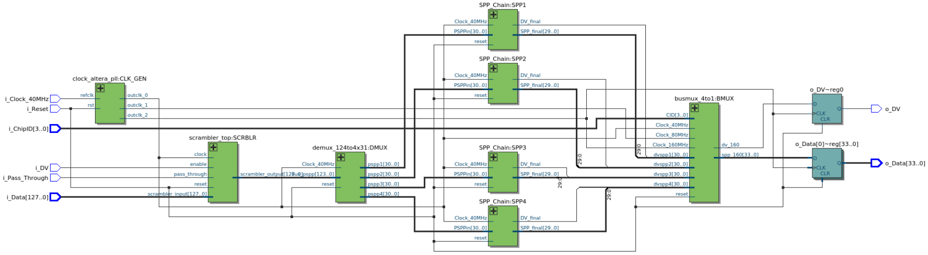
- Peak total data rate out of the upgraded VELO can reach 3.6 Tbit/s.
- VeloPix readout is continuous and Zero Suppressed.
- HLT can not deal with that volume.
- Data processed in FPGAs before HLT.
- First prototype available: AMC40.



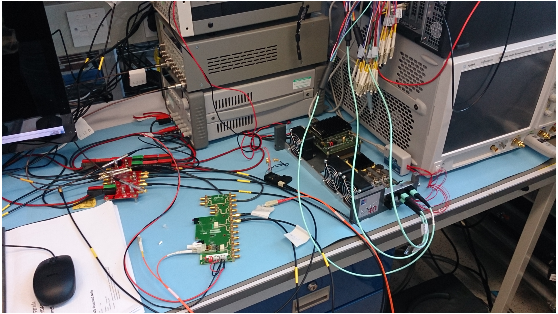
DAQ

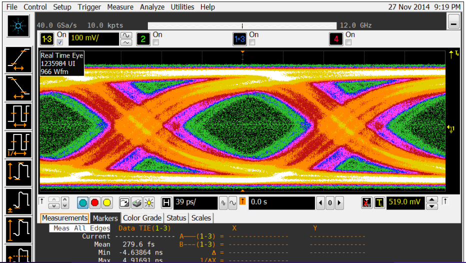
GWT serializer

- AMC40 will be common for all the LHCb detectors ... but VELO.
- Data packets based on serializer chip (GBT) not compliant with VELO requirements.
- Modifications in the FPGA firmware must be developed.
- Replacement chip (GWT) to be tested in December.
- VHDL code ready (by Graham Miller and myself).



DAQ

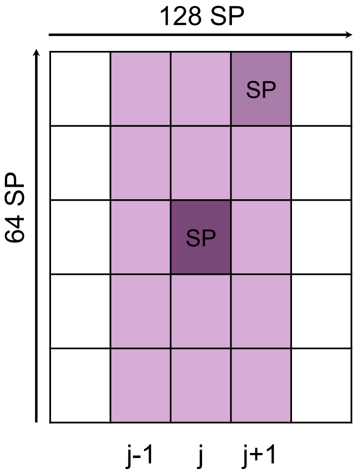



File Control Setup Trigger Measure Analyze Utilities Help
27 Nov 2014 9:19 PM
40.0 GSa/s 10.0 kpts
12.0 GHz
1-3 On 100 mV/
2 On
1+3 On
4 On
Real Time Eye
1235984 UI
966 Wfm
39 ps/
0.0 s
519.0 mV
Measurements Markers Color Grade Status Scales
Meas All Edges
Data TIE(1-3)
X
Y
Current
Mean 279.6 fs
Min -4.63864 ns
Max 4.91691 ns
A---(1-3) =
B---(1-3) =
Δ =
1/ΔX =

Data processing

Data processing

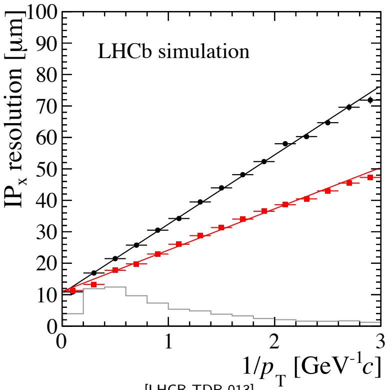
- AIM: include clustering in the FPGA.
- Data frame includes hitmap of 4x2 pixels (SP).
- Sort data according to spatial data (Parallel bubblesort).
- Check if SP is isolated, add an isolation flag.



By Stefanie Reichert.

Impact Parameter

- Plot shows impact parameter resolutions and momentum distribution
- Improvement between current (black) and upgrade (red) VELOs
  - Due to low material (RF Foil and modules) and smaller beam distance

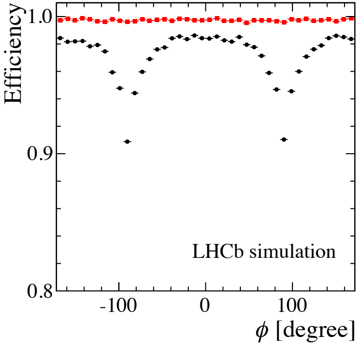


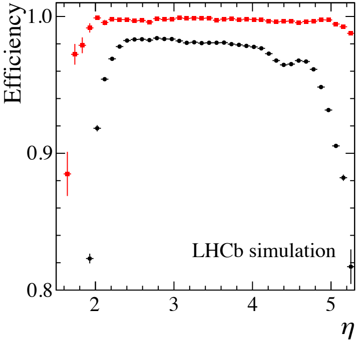
[LHCB-TDR-013]

By Thomas Bird

Tracking Efficiency

- Tracking efficiency with upgrade conditions, $L = 20 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Current VELO (black) and upgrade VELO (red)
- High occupancy in strip detector causes many ghost tracks





[LHCB-TDR-013]

By Thomas Bird

Simulations

Silicon simulations

- Kevin Maguire and Jon Harrison.
- Currently the diffusion of charge is modelled numerically with a random number generator.
- Goal: simulate analytically the charge diffusion in the silicon.
- Based on a previous work from Daniel Hynds.

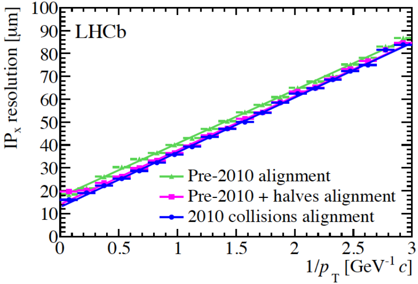
Charm triggers

- By Jolanta Brodzicka.
- Fact: we won't be able to save all the charm produced.
- Deciding relevant modes.
- How to prescale (if needed).
- What to sacrifice if the bandwidth for the charm gets too limited.

Alignment

Alignment

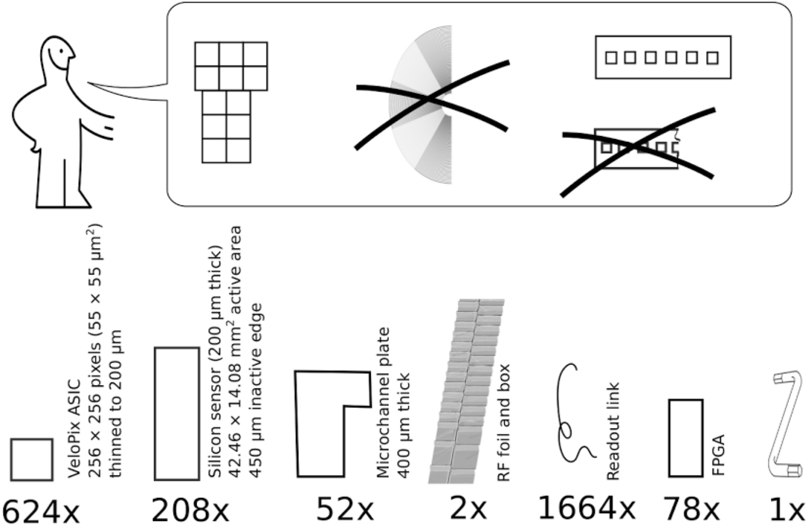
- Alignment is an essential element to get the best performance
- Allows precision better than the single hit resolution.
- Based on a kalman filter method.
- Expected main change during the data taking: 2 half aligment
  - due to the 2 half movement at the beginning of each fill.
- Track sample for the 2 half alignment: tracks traversing both halves of the detector
  - Large sample thanks to the L layout.
  - Overlap between the two sensors on either side of the module to 2 pixels.



By Silvia Borgi and Christoph Hombach.

Conclusions

VELÖ UPGRADE



Conclusions

Manchester contributions

- UoM have a leading role in the construction of the VELO upgrade.
- Big effort in equipment and manpower.
- RD on glue.
- FPGA.
- Assembly.
- QA.
- Simulation.

Thank you for your attention

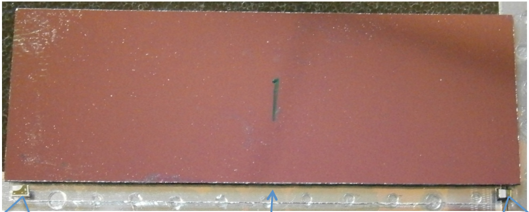
Especial thanks to the people who contributed with slides

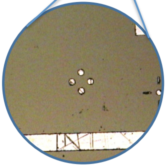
Stefano deCapua, Julian Freestone, Chris Parkes.
Silvia Borghi, Jolanta Brodzicka, Andrew McNab.
Suzzane Klaver, Thomas Bird, Kevin Maguire, Jon Harrison, Stefanie Reichert.
AntoniShtipliyski, Guy Stelmasiak, James Potts, Lorenzo Capriotti.

Backup Slides

Assembly

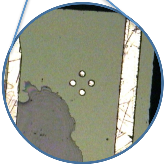
4 ‘detector assemblies’ prepared.





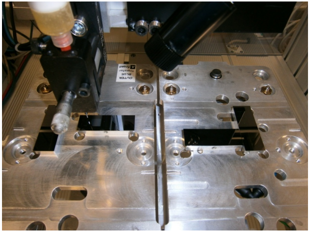
Silicon *‘sensor’* 300 μm thick glued to Glass *‘ASICs’* 300 μm thick

Corners containing dot pattern fiducial marks, cut from Atlas SCT wafers, glued to glass

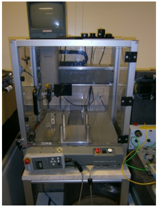


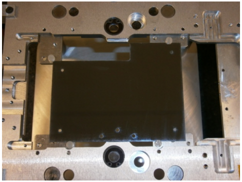
Assembly

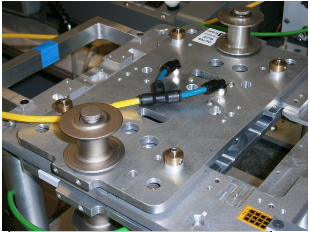
Gluing and assembly



Both transfer plates are supported on our robot platform and a pattern of glue dots applied (Araldite 2011)







Finally all plates are brought together and held with spring clamps

Shear force test: temperature vs time