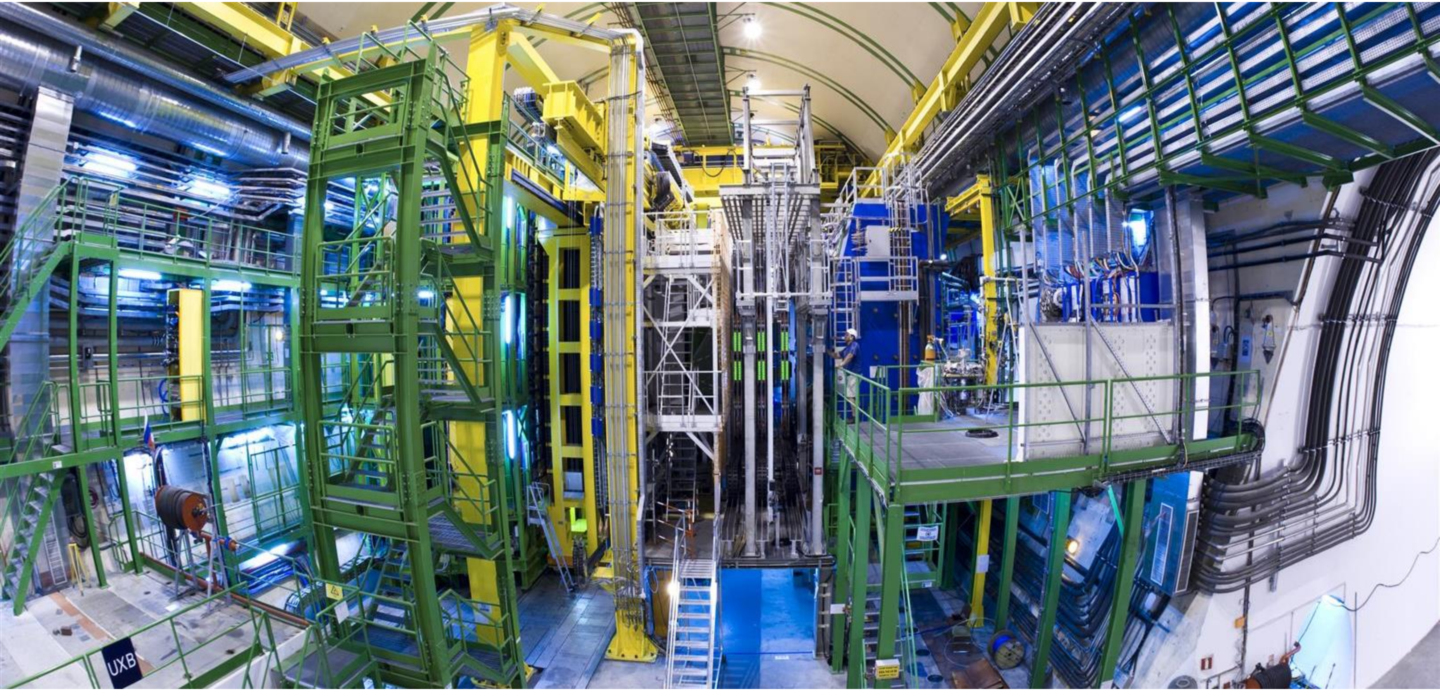
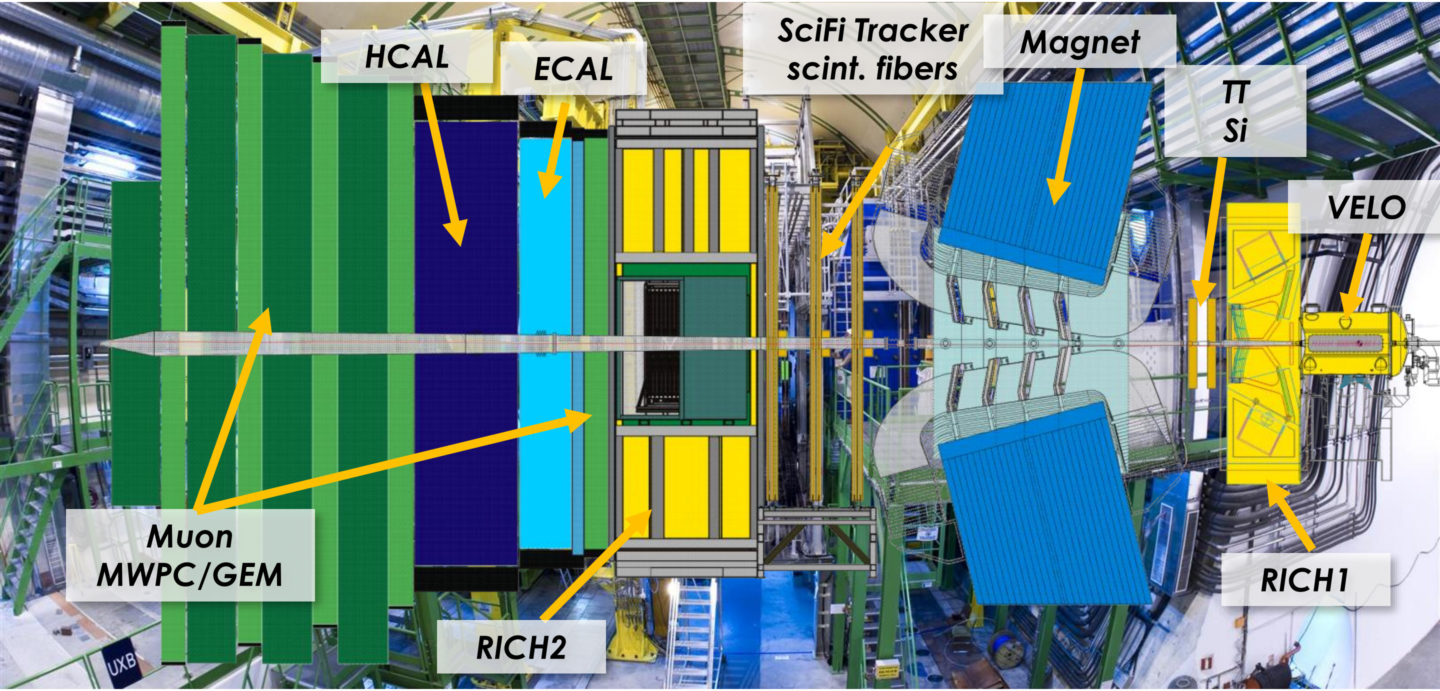
Upgrades of the LHCb Vertex Locator

Kazu Akiba on behalf of the LHCb VELO

The LHCb Experiment



The LHCb Experiment



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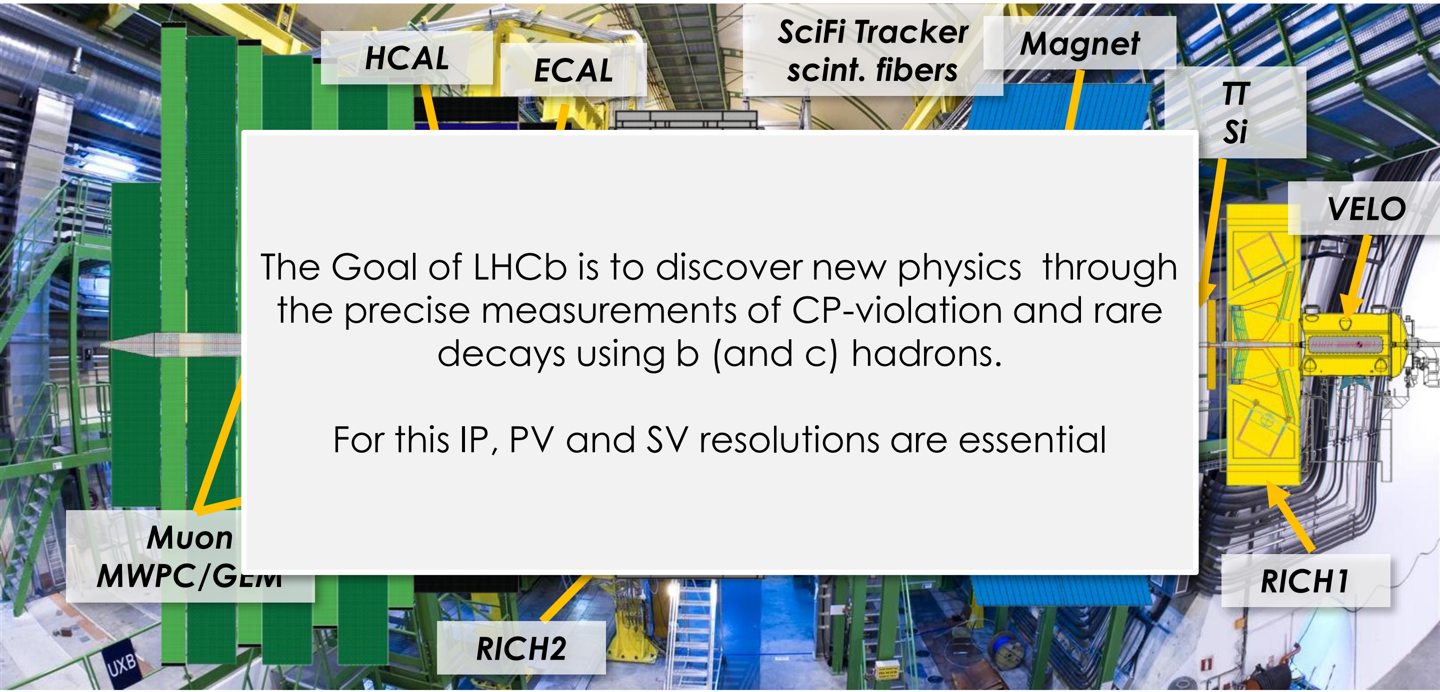
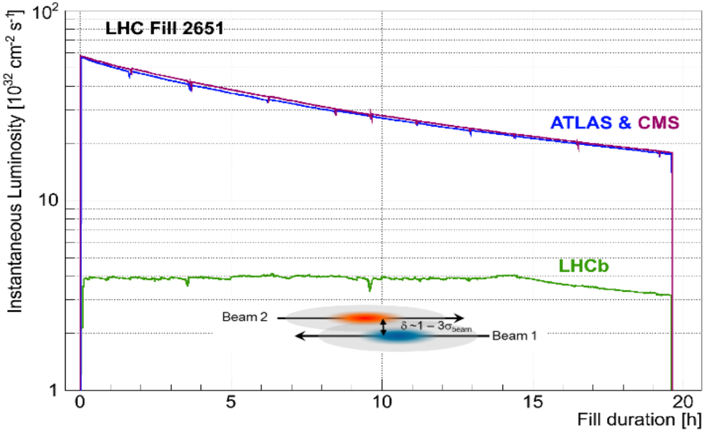


The Goal of LHCb is to discover new physics through the precise measurements of CP-violation and rare decays using b (and c) hadrons.

For this IP, PV and SV resolutions are essential

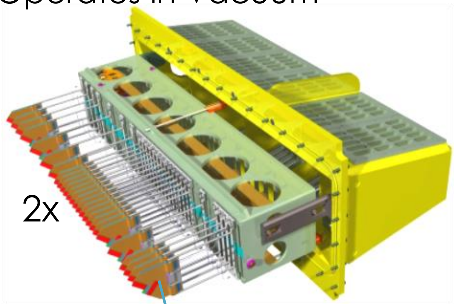
LHCb Upgrade

- LHCb upgrades to look for more **collisions/s** in order to select the most interesting ones.
- Smart trigger algorithms to increase the yield of **hadronic decays** and more luminosity for **rare decays.**
- The LHCb Upgrade increases the **luminosity (x5)** and the **readout rate (x40)**.
- This means more radiation damage, more occupancy, more data to transport.



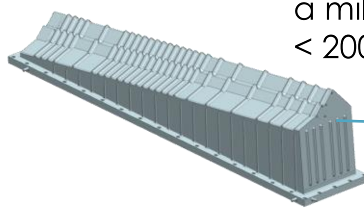
Overview of the Velo upgrade

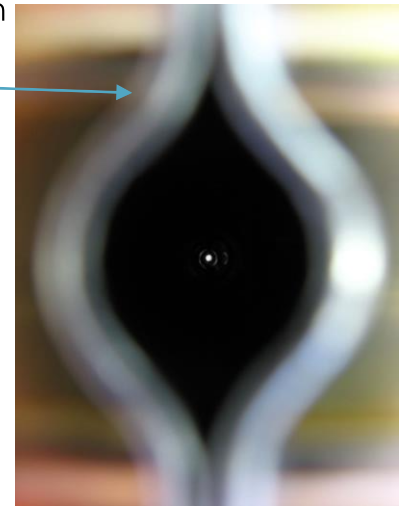
52 modules, 40 Mpixels
Operates in Vacuum

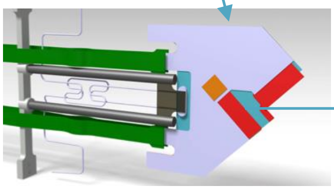


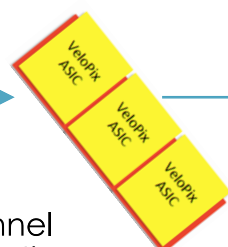
2x

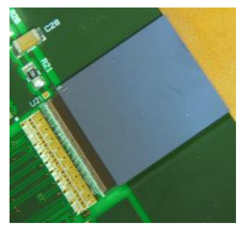
5.1 mm sensitive distance to beam.
Separated from the beam by a milled box at 3.5 mm
< 200 μm thin









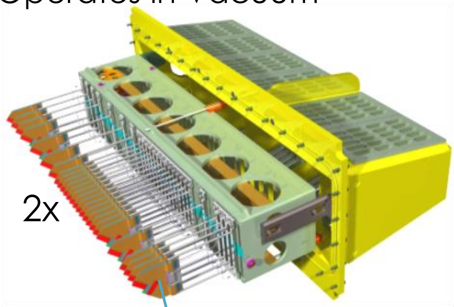


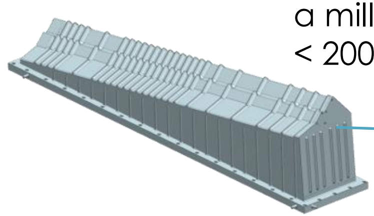
- Innovative micro-channel cooling (-30 °C) also acting as the module substrate

VeloPix ASIC
Data driven readout @20 Gb/s

Overview of the Velo upgrade

52 modules, 40 Mpixels
Operates in Vacuum





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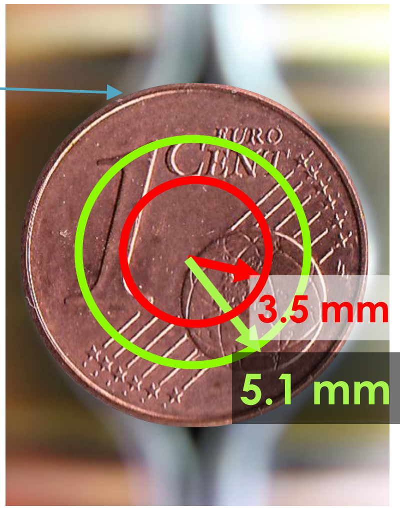
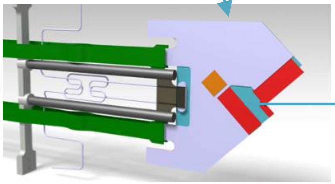
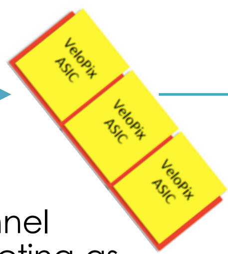
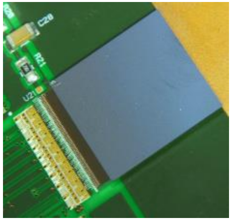








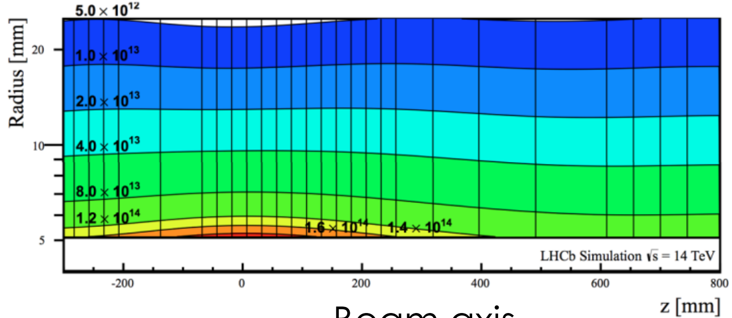
- Innovative micro-channel cooling (-30 °C) also acting as the module substrate

VeloPix ASIC
Data driven readout @20 Gb/s

Sensor Development

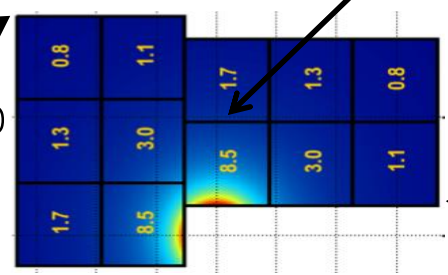
- Requirements:
- Collect ***6000 e⁻/MIP***
  – *99% eff* at ***370 Mrad***
  ~ 8 x 10¹⁵ 1 MeV $\boldsymbol{n_{eq}/cm^2}$.
  <u>this is equivalent to 5 years of LHCb Upgrade ***50 fb⁻¹***</u>
  - The ATLAS IBL – at 550 fb^{-1} – expects 3.3 x 10^{15} 1 MeV n_{eq}/cm^2 or 160 MRad.

Non Uniform radiation exposure



Beam axis

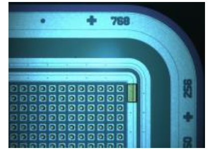
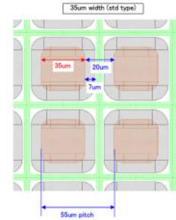
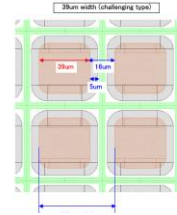
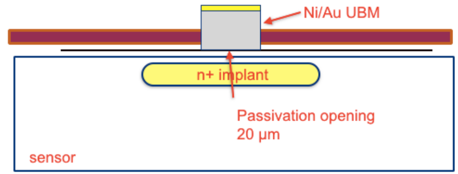
- Timepix3 ASIC bonded to the prototypes
  - TOT allows charge measurements.

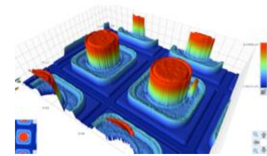


Sensor Prototypes

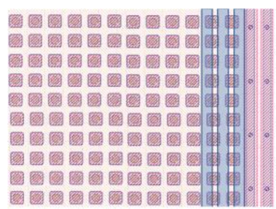
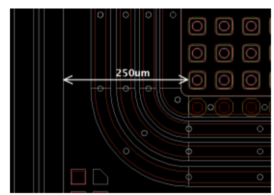
- Prototyping round quite some variants:
- Hamamatsu:
  - n-on-p 200 µm thick
  - 450 and 600 µm PTE
  - 35 and 39 µm implant
  - UBM
- Micron :
  - n-on-n and n-on-p
  - 36 µm implant
  - 150, 250 and 450 µm PTE

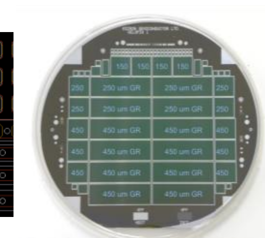
Hamamatsu



Micron

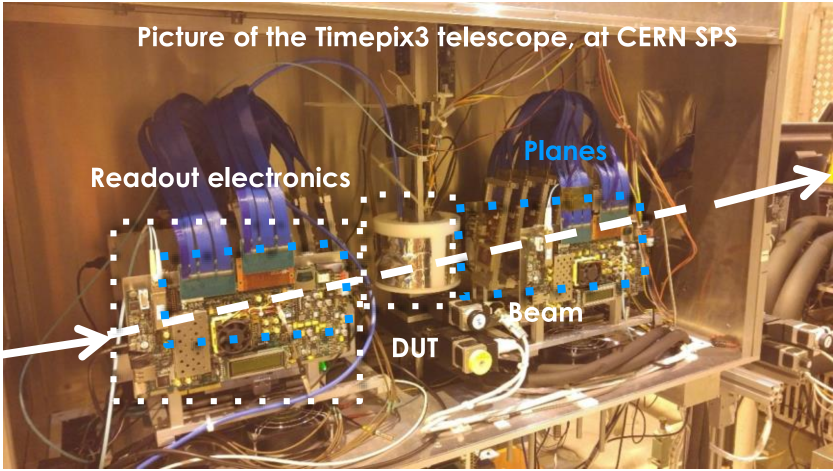


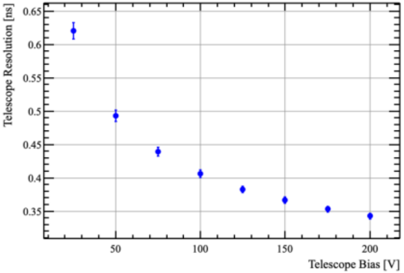
Testing prototypes with SPS beam

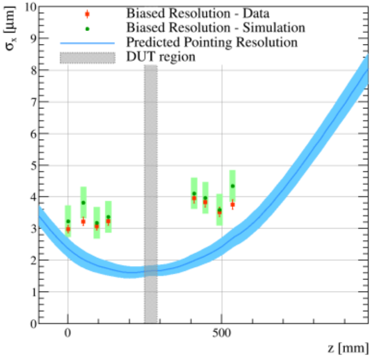
- Using **Timepix3** telescope
- 4 Timepix3 on 2 "arms"
- pointing resolution below **1.6 µm**
- Precise **time stamps (1.56 ns)** yield a clean Pat. Rec.
- 350 ps track time resolution

- **JINST 14 (2019) no.05, P05026**

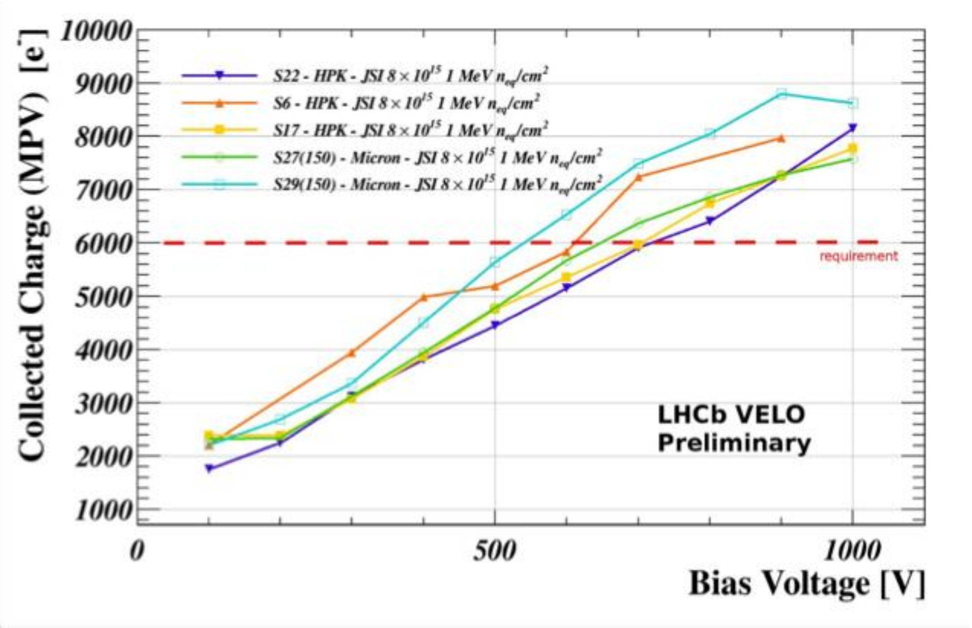
- *Poster #285: improved track time resolution from 350 ps to 270 ps.*







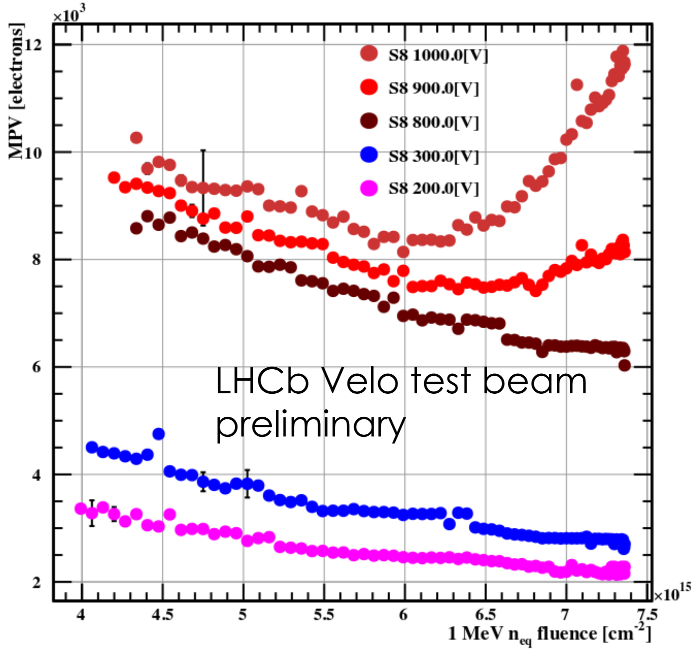
Collected Charge – neutron irradiated



- Typical threshold of 1000 e^-.
- Even if the charge is shared up to 6 pixels the signal would cross the threshold.

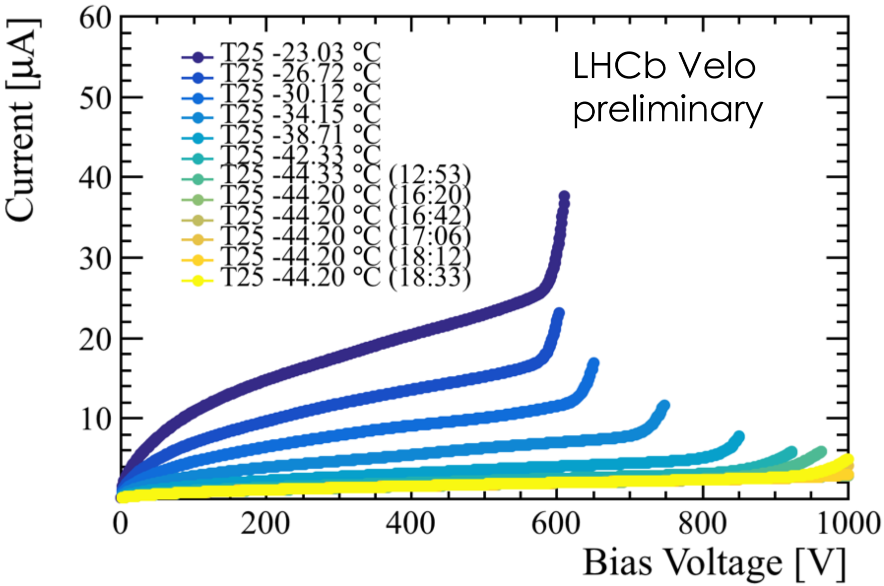
Charge Multiplication – IRRAD

- Heavily irradiated regions show higher charge collection at the same voltage.
- The effect increases with the voltage.
- Still under analysis

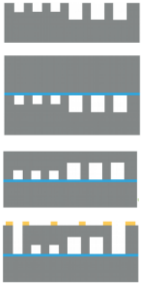


Temperature dependent Breakdown

- Some sensors show early breakdown which is temperature dependent.
- This effect seems slightly mitigated after some time biased.
- Operate at lower temperatures to gain radiation hardness?



Microchannels etched in silicon

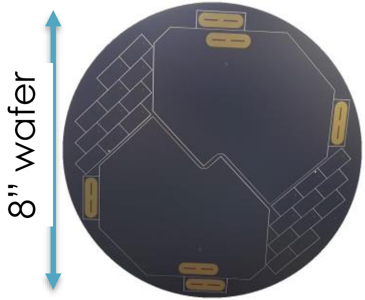


Channel etching

Cap wafer bonding

Thinning (both sides)

Inlet/Outlet etching

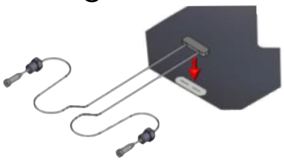


Silicon pre-tinning

+

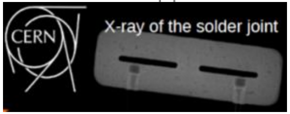
+

Alignment



Soldering

+



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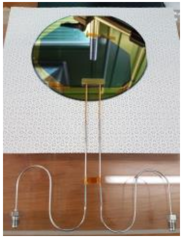
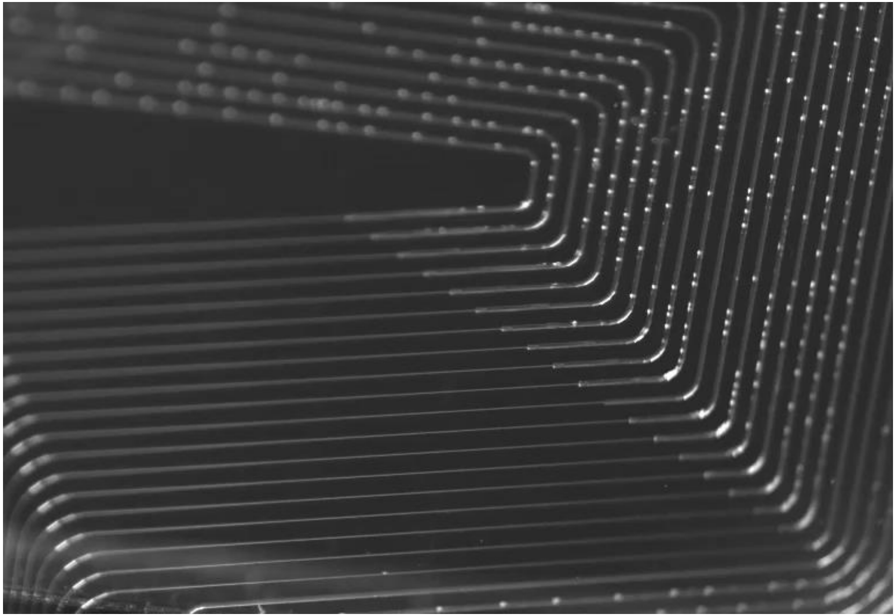


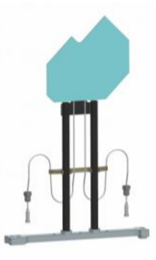
Final assembly can
Withstand 200 bar

Complex engineering feat – full description on poster #299

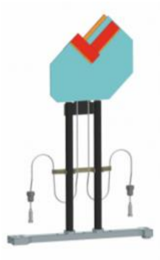
boiling CO_2 cooling



Module Production



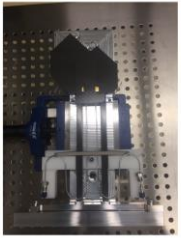
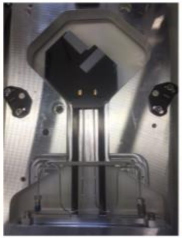
Mechanical construction

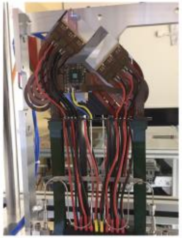


Precision tile placement to 10 μm

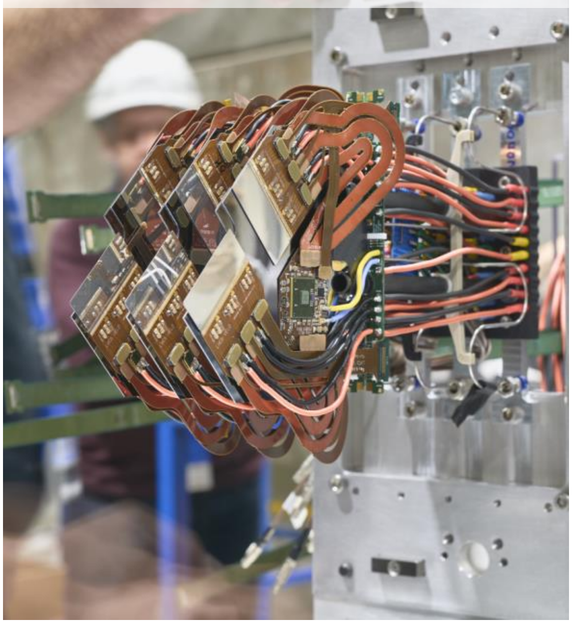
Flex circuit placement

wire bonding and HV/LV/data cable attachment

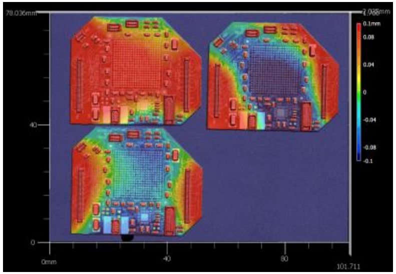


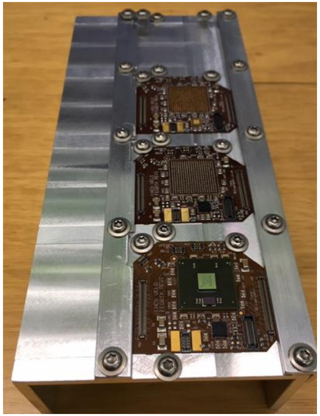
Three modules in SPS test beam



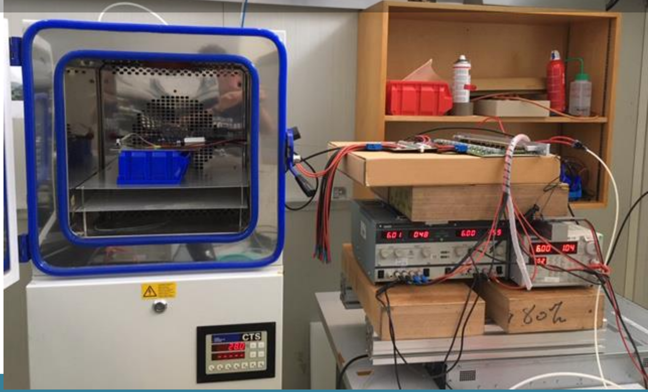
Gbtx problems

- Non-flatness of the PCB leads to imperfect bump-bonding of GBTx
- Thermal stress causes some bonds to disconnect at -32°C
- Reflowing the PCBs improves the situation, but does not solve it
- Redesigned the layer stack-up of the PCB + new via technology
- Use a jig to keep PCB at while bonding GBTx



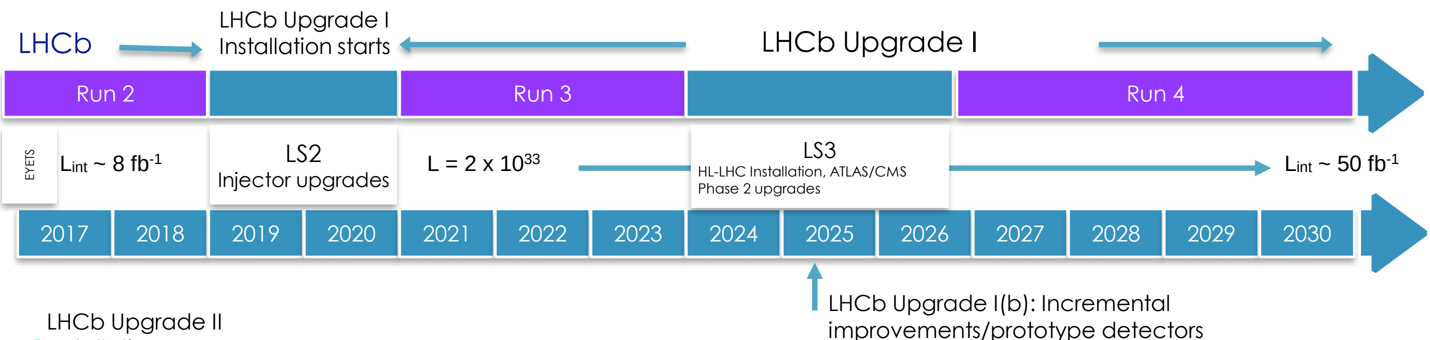


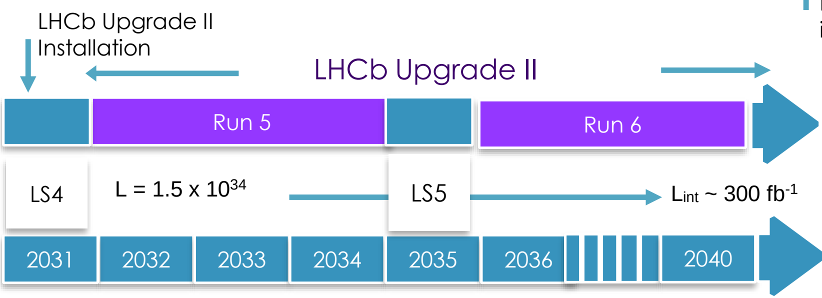
- prototype modules loose communication when cooled.
- GBTx cannot re-lock if clock is lost below -10°C
- Increasing the operating current increases probability to successfully lock onto clock.
- Required to increase the charge-pump current in the phase control of the VCO.
- Default: 1.5μA
  Set: 5.625μA

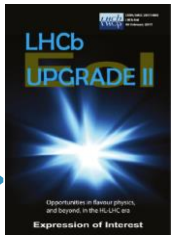


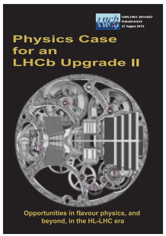
Climate chamber used for the tests

Preparations for upgrade II









LHCb Upgrade II
Run 4 and Run 5
2030 ++
Accumulate
250-350 fb^{-1}

LHC parameters for Upgrade II

Baseline (nominal) beam parameters and levelling at IP1&5

- Range of potential solutions to operate LHCb Upgrade II at up to 1.5×10^{34} $cm^{-2}s^{-1}$
- Horizontal and vertical crossing angle scenarios under consideration
- Number of colliding bunches at IP8: 2572
- Levelling by parallel separation at IP8
- reduction of yearly integrated luminosity at IP1&IP5 - 1% - 2.5%

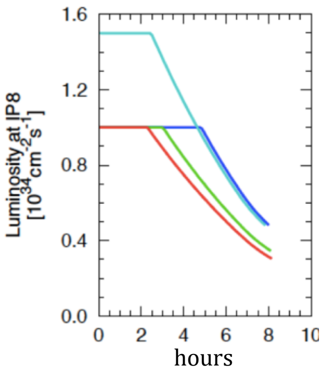
$$\sigma_z^{RMS} \approx 44.7 \text{ mm}$$

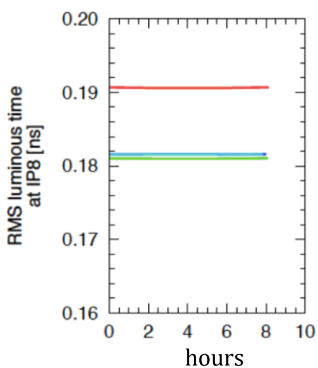
$$\sigma_t^{RMS} \approx 186 \text{ ps}$$

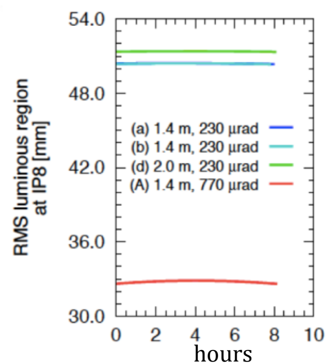
$$\sigma_t^{comb} \approx 240 \text{ ps}$$

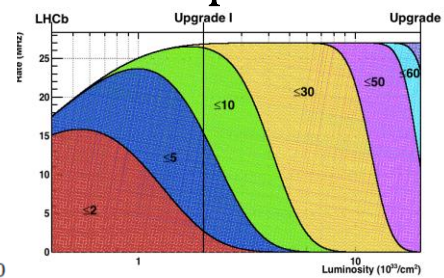
$$\text{Visible collisions} \approx 42$$

$$\text{Pile up} \approx 60$$









LHC parameters for Upgrade II

Baseline (nominal) beam parameters and levelling at IP1&5

- Range of p
- Horizontal c
- Number of
- Levelling b
- reduction c

≈ 44.7 mm

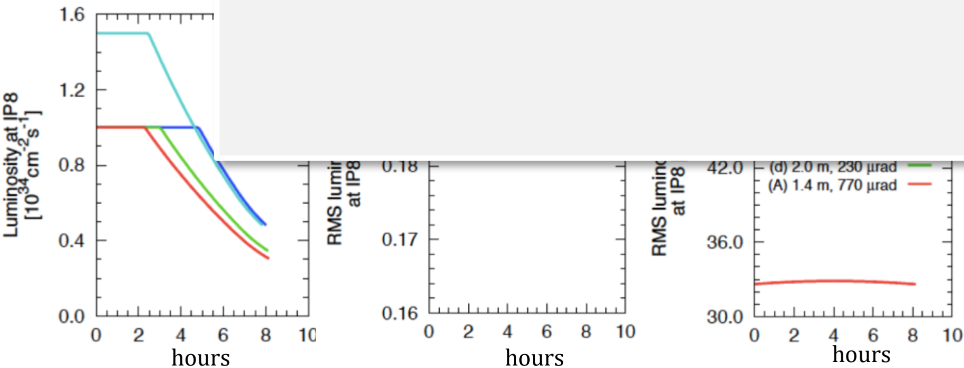
≈ 186 ps

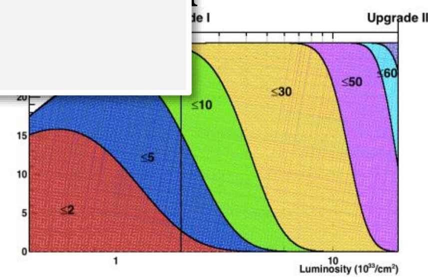
≈ 240 ps

ions ≈ 42

p ≈ 60

For LHCb physics' goals it's essential to identify the origin collision vertex of the b/c mesons.

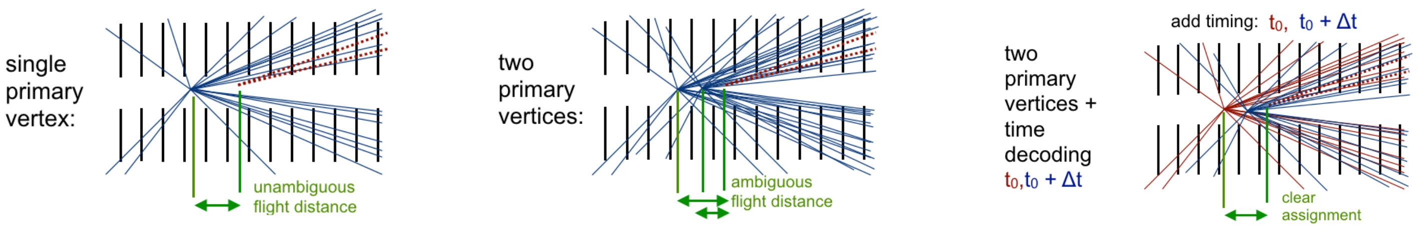




4D tracking and vertexing

Move towards **4D** tracker concept with addition of **hit timing**:

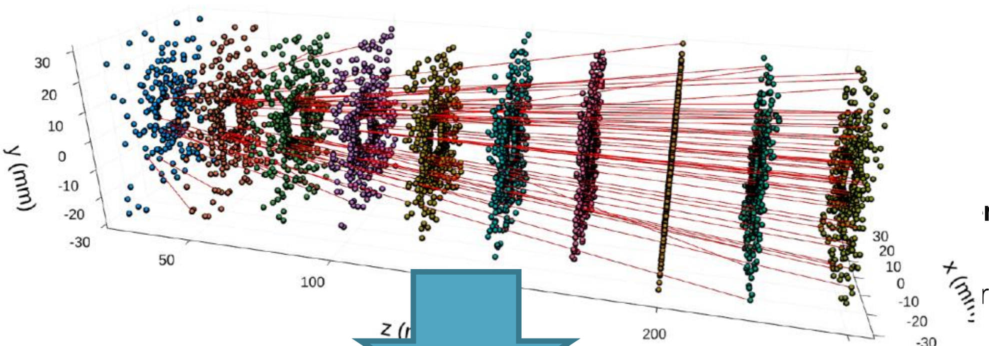
- Real time track reconstruction critical for Upgrade I and II: **Only High-level Trigger**
- Timing information will contribute to **Pattern Recognition** speed and efficiency
  - **Track time stamping** for PV association, PV timing, and combination with downstream detectors for beam gas and background control, calorimetry and time of flight



4D tr

Move tow

- Real tim
- Timing infc
  - **Track ti** detectc



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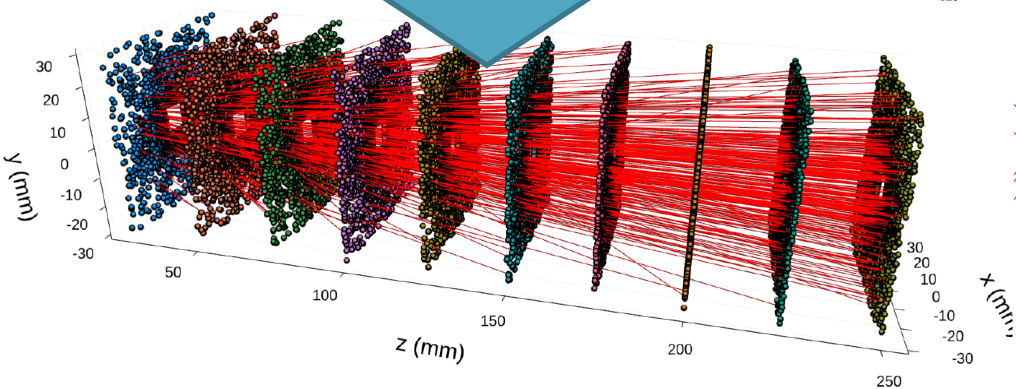
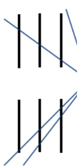
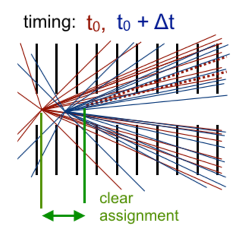
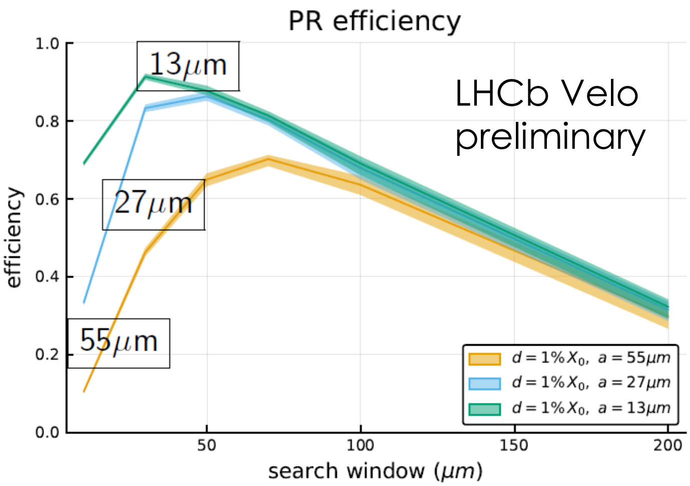


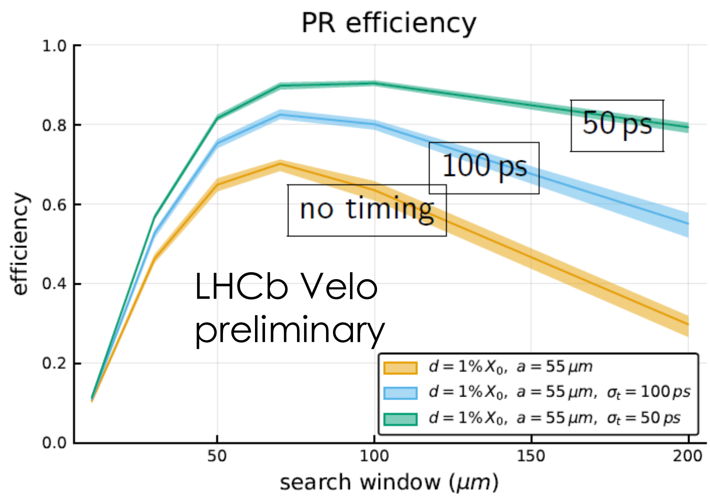
single primary vertex:



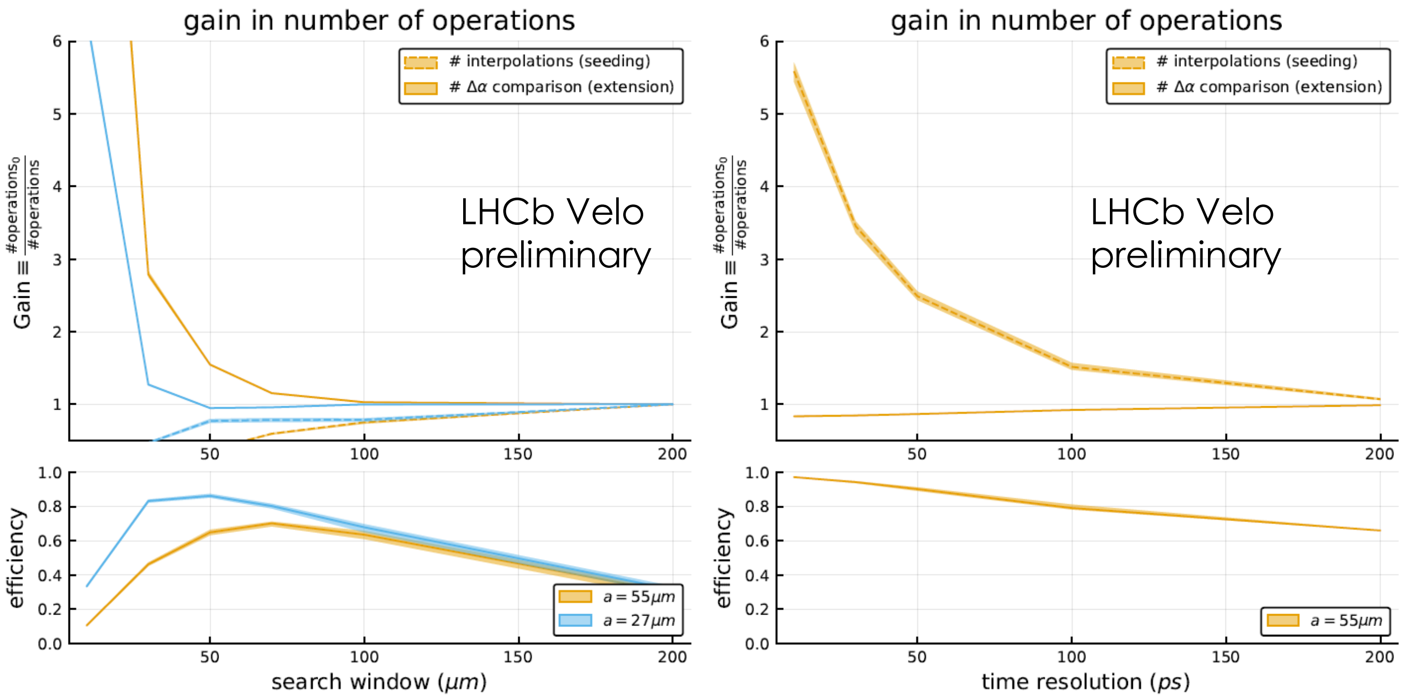


Pattern recognition improvement



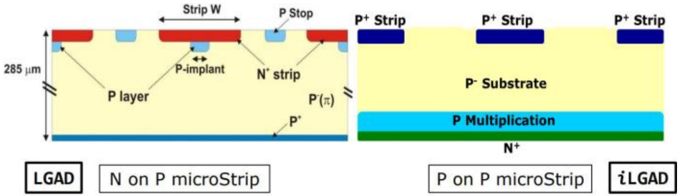


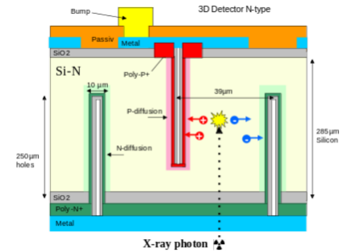
Timing gain

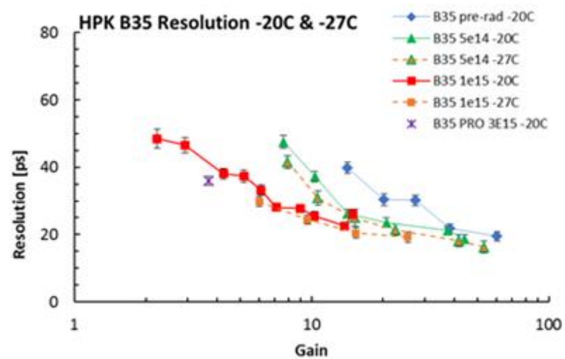

gain in number of operations
interpolations (seeding)
Δα comparison (extension)
LHCb Velo preliminary
Gain ≡ #operations0 / #operations
efficiency
a = 55μm
a = 27μm
search window (μm)
gain in number of operations
interpolations (seeding)
Δα comparison (extension)
LHCb Velo preliminary
Gain ≡ #operations0 / #operations
efficiency
a = 55μm
time resolution (ps)

Sensors

- Sensor R&D considering:
  - Thin planar
  - LGAD and iLGAD
  - 3D concepts
- Starting an evaluation programme using Timepix4 as a prototype FE.
  - 200 ps TDC
- Final temporal resolution under consideration between 20 and 200 ps per hit.
- Many manufacturers shown prototypes: CNM, FBK, HPK…
- How to achieve this resolution with small pixel devices?







Future ASIC challenges

- Cope with increase in Radiation damage
- Analog front-end does not scale much -> about the same size as VeloPix/Timepix4 (30% of pixel)
- Cope with hit pile up:
  - @Upgrade I, MIP discharge time ~300 ns for 1% max pileup.
  - Upgrade II would need 10 times faster rate.
- Per pixel TDC with time resolution < 50ps.
- More information in output and higher hit rate.
- Time-walk correction?
- Clock distribution effects?

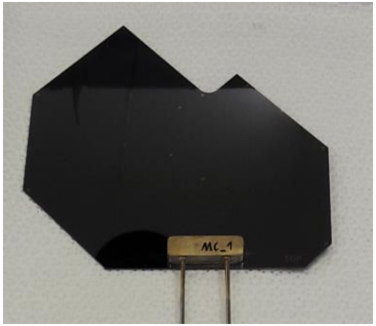
	VeloPix (2016)	Timepix4 (2019)	Velopix2 (202?)
technology	130 nm	65 nm	**28 nm**
Pixel size	55x55 μm^2	55x55 μm^2	**55x55 μm^2**
Sensitive area	2 cm^2	7 cm^2	**2 cm^2?**
Packet size	24 bit	64 bit	**64 bit?**
Max rate	400 Mhits/cm^2/s	180 Mhits/cm^2/s	**4000 Mhits/cm^2/s**
Time resolution	25 ns	200 ps	**20-50 ps?**
Output data rate	20 Gb/s	81 Gb/s	**500 Gb/s?**

- Fruitful collaboration with the Medipix group has yielded the VeloPix ASIC for the LHCb Upgrade I.
- the Timepix4, with impressive fast timing capabilities is scheduled to appear soon.
- LHCb Upgrade II requirements more demanding still but could draw on similar concepts

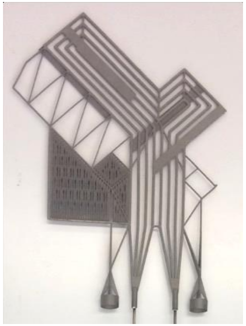
Cooling for next upgrade

- Operation in vacuum demands active cooling.
- Microchannel approach could be too complex if a replacement is planned.
- Studying the possibility to operate at lower temperatures < -30°C
  - Avoid runaway at high radiation damage
  - Mobility gets better at low temperatures
  - Requires the R&D of different cooling fluids…

General needs: lightweight, possibly partially replaceable modules and mechanics



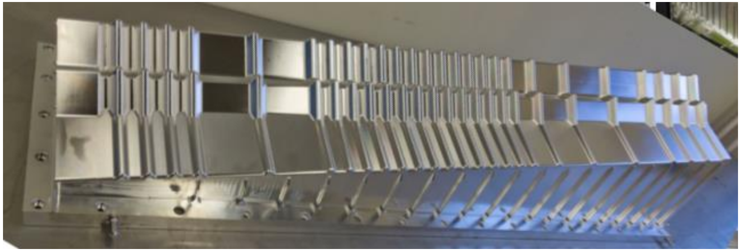
Micro channels could get cheaper



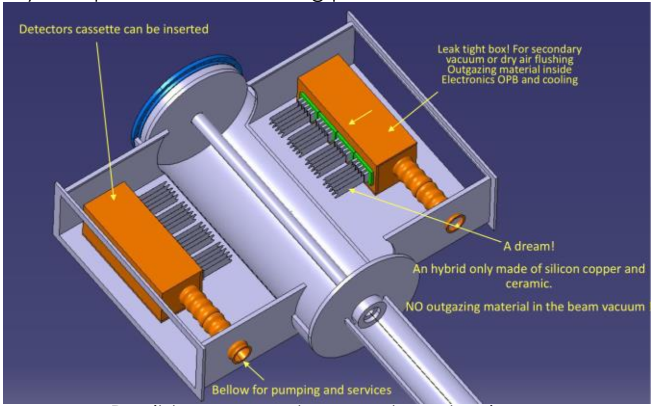
3d printed Titanium substrates, already prototyped for Upgrade I

Mechanics

- RF box construction is a very complex and demanding procedure.
- **No foil** would be the ideal design.
- Issues:
  - Outgassing detectors.
  - Harmful wakefield
  - Beam impedance.
- Construction without a foil also makes more difficult to replace detectors.



RF+Vacuum Box milled out from an Aluminium block.
Very complex and demanding procedure.



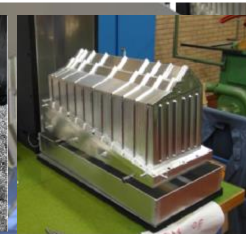
Possible sensor replacement mechanism

Mechanics

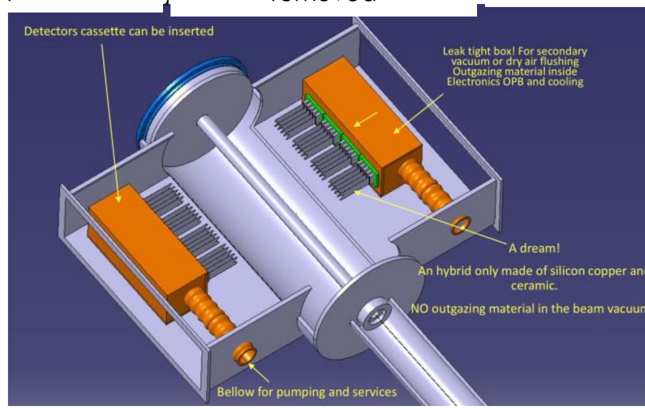
- RF box construction is a ve complex and demanding procedure.
- **No foil** would be the ideal design.
- Issues:
  - Outgassing detectors.
  - Harmful wakefield
  - Beam impedance.
- Construction without a foil also makes more difficult to replace detectors.

Initial solid forged Al alloy block

>98% of material removed



Internal mould support during machining steps



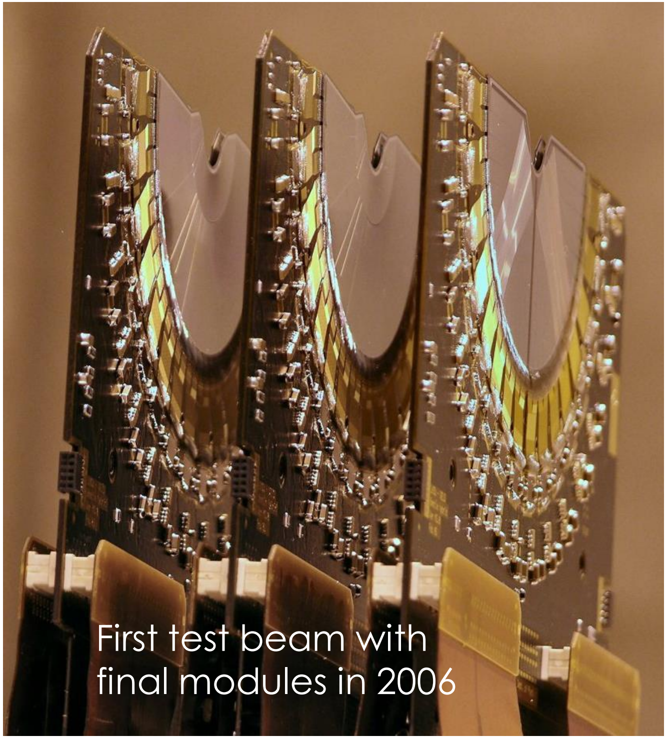
Possible sensor replacement mechanism

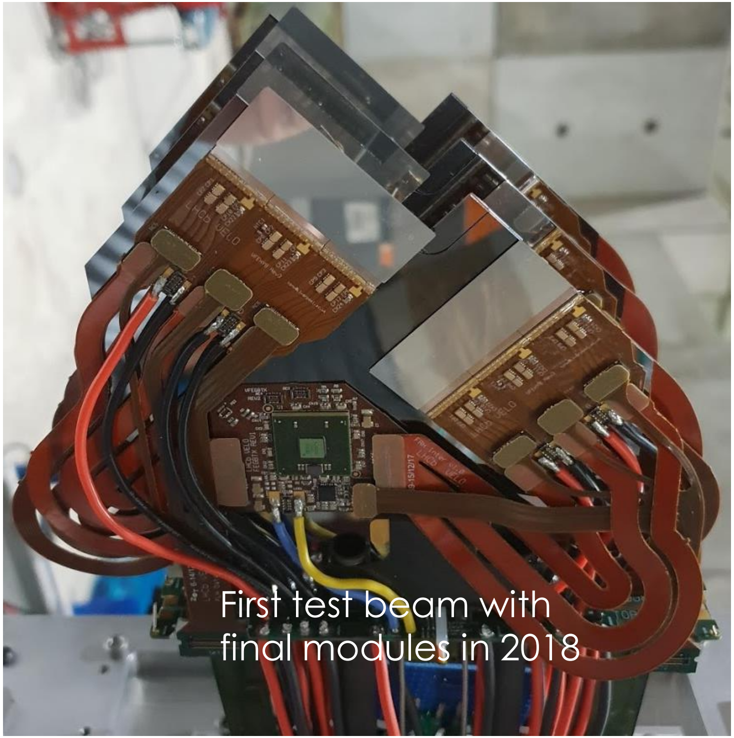
Summary

- Final items for the upgrade produced.
- Modules being assembled
- Mechanical installation has already started

- We are also planning a next upgrade to run at up to **10 times higher** instantaneous luminosity.
  The high Primary Vertex density motivates a Vertex detector with **high resolution timing**.
- Fast timing shows promising results in the **pattern recognition** as well.
- An ultra **high radiation** resistant **sensor** and **ASIC** technology is required to operate through the whole lifetime.
- Alternatively a suitable **replacement strategy** drives mechanical technology R&D.

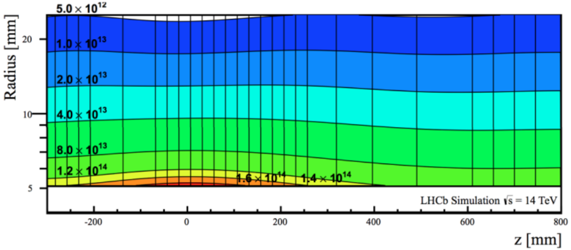
Back up

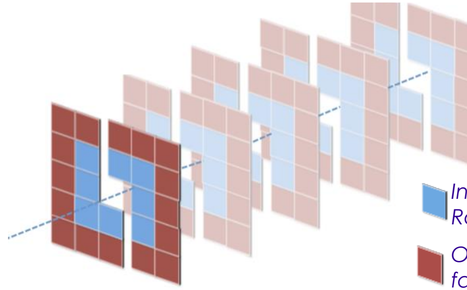

First test beam with
final modules in 2006


First test beam with
final modules in 2018

Design considerations – Radiation

- At 5 mm, fluence translates to :
  1.6 x10^{14} 1MeV n_{eq}/fb.
  after 300/fb➔ ~5 x10^{16} n_{eq}
- Very challenging constraint for fast timing devices.
- A dual technology system could combine radiation hardness at the inner part and timing resolution at the outer region.
- Planning for a replacement could allow a less resistant sensor technology.

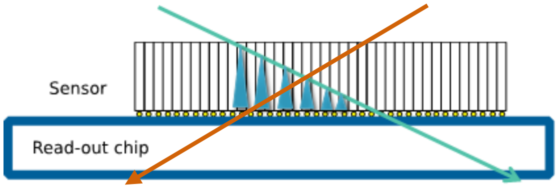


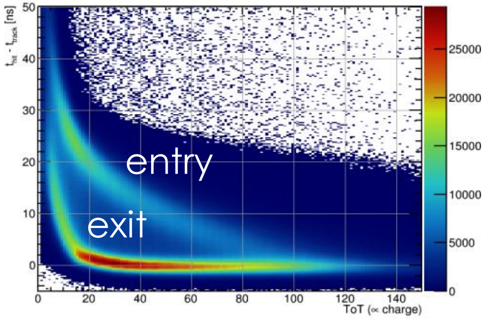


Possible design with 2 technologies: outer sensors with better timing but lower radiation resistance.

Timing experience: Timepix3

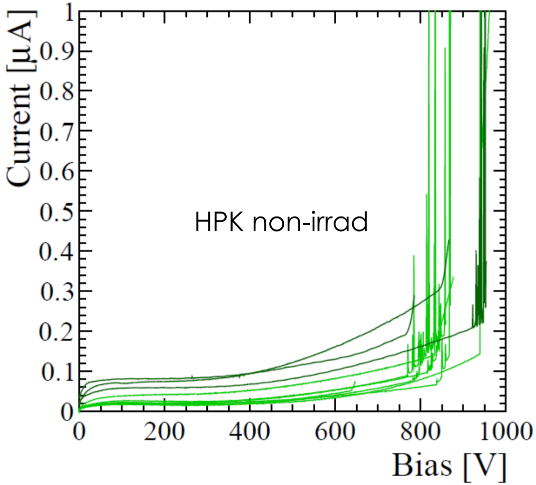
- Timepix3 telescope experience shows that "4D" tracking is the way forward.
- The telescope shows virtually no ghost track in the 10 ns window used in the reconstruction.
- Possible to calculate the slope inside the ASIC in a cluster: every cluster would be also a stub.

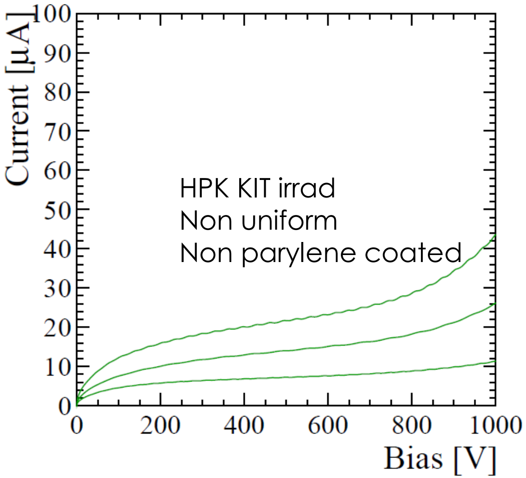




Timepix3 Telescope

HV Tolerance

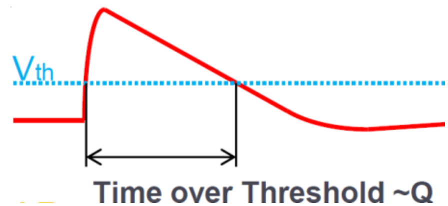


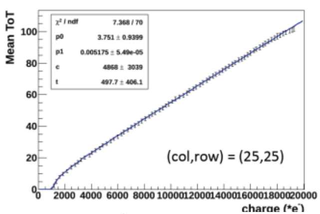


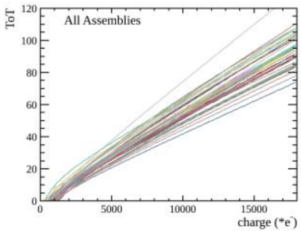
Sensors tested in vacuum.

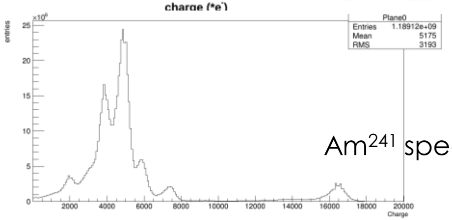
Timepix3 – charge measurement

- The ***calibration of the charge measurement*** has to be well understood, in order to compare different prototypes, and also at various irradiation levels.







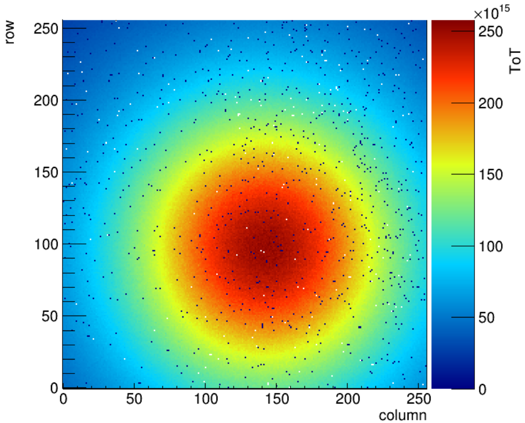


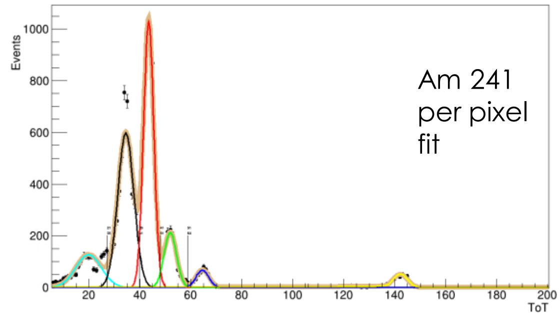
Am^{241} spectrum

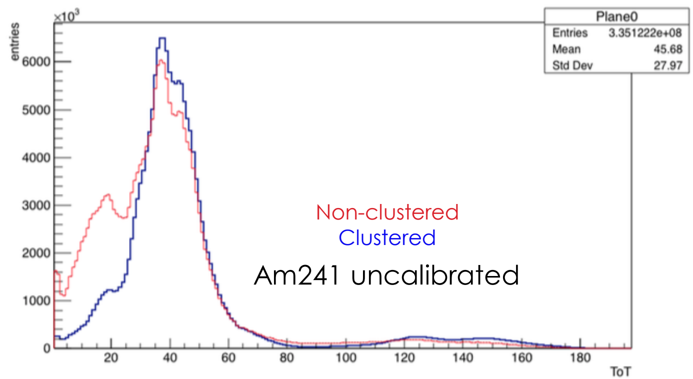
- ***Timepix3 is the ideal tool:*** very precise and easy charge collection measurement
  - ***Timepix(1) is not radiation hard.***
  - ***Medipix3 requires slow (tedious) threshold scans***
  - ***Velopix is not out. And it's binary.***
- ***←But requires tuning and calibration.***

Charge calibration

- Verified with radioactive sources:1 week exposure

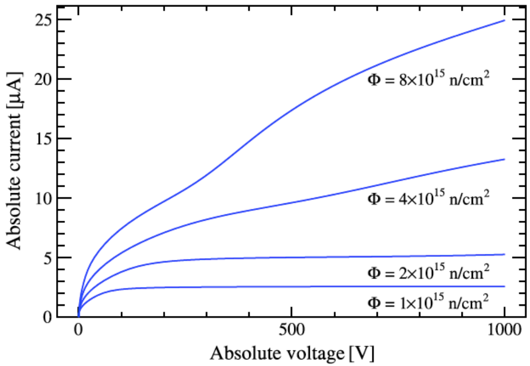


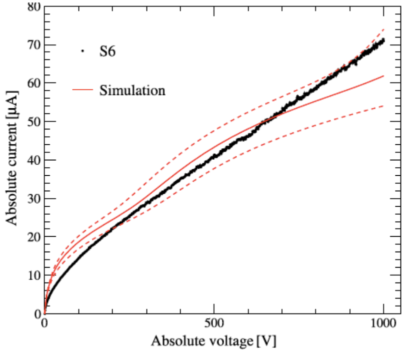




IV Model

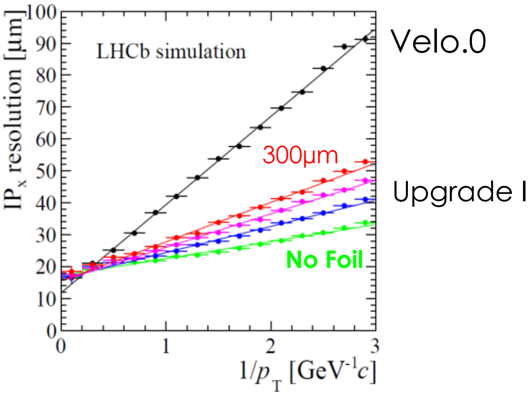
- Current generated due to avalanche in the sensor.
- Avalanche is proportional to the radiation damage.
- (Shot noise increases with temperature and induces breakdown)*
- Related to the charge multiplication

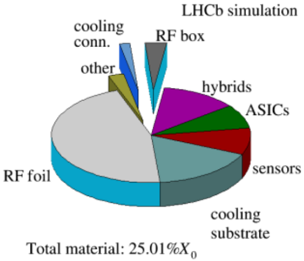


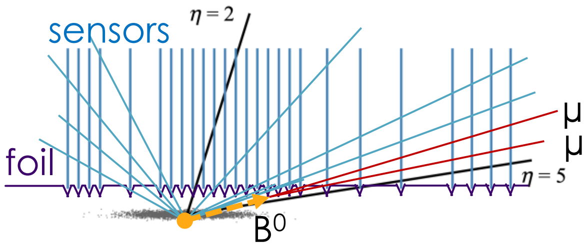


Foil

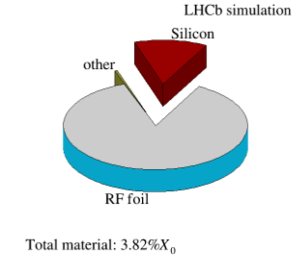
- Separation from primary LHC vacuum introduces material which degrades the IP performance
  - physics performance benefits from no foil.





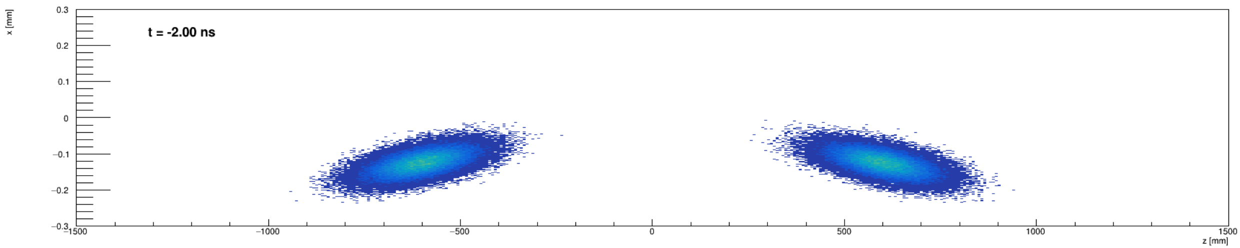


Design minimizes material before 2nd hit and extrapolation distance.



Foil is the biggest contribution before second hit

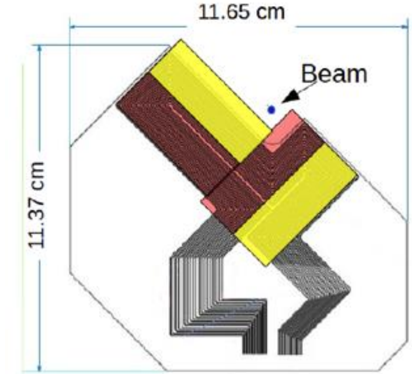
Same space, different time

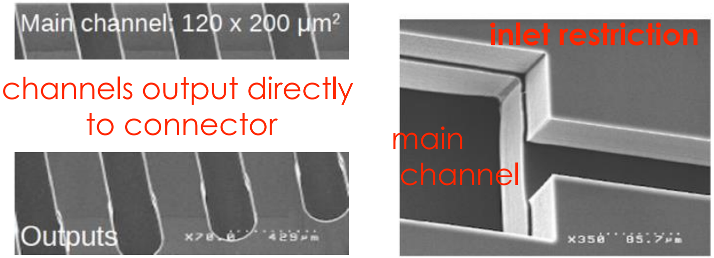


Microchannel cooling

- Efficient cooling solution is required to maintain the sensors at < -20°C
- No CTE mismatch
- This is provided by the novel technique of evaporative CO_2 circulating in 120 µm x 200 µm channels within a silicon substrate.

Two step channel etching





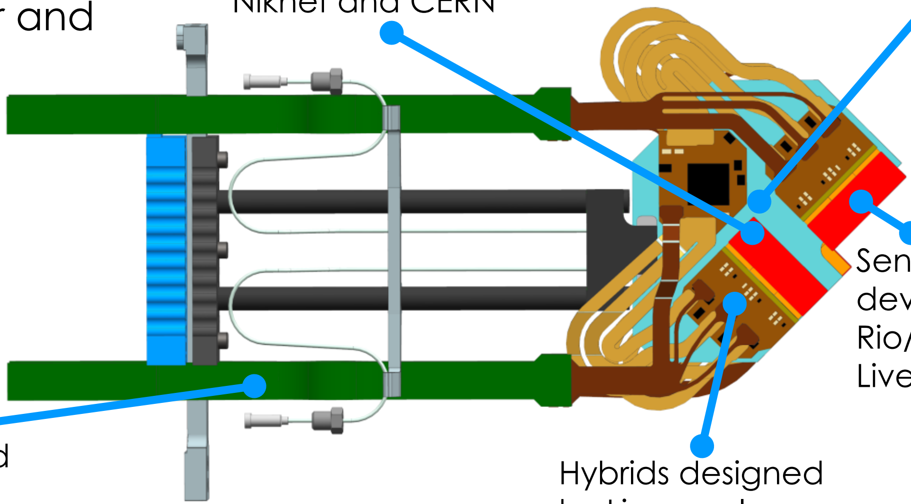
SEM images of etched wafer before bonding

Modules

Modules to be built in Manchester and Nikhef

ASICs created by Nikhef and CERN

Microchannels developed by CERN and Oxford



Sensors developed by Rio/CERN/USC Liverpool

Hybrids designed by Liverpool

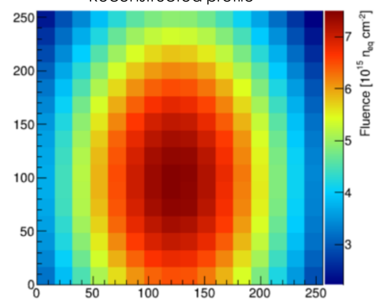
Ultra high speed copper links developed in Glasgow

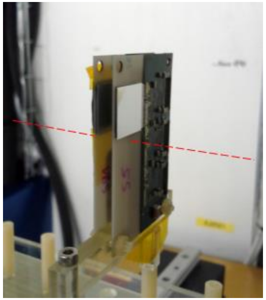
Irradiation

- Sensors were irradiated at
  - JSI/IST (n/reactor)
  - KIT (26 MeV p/beam),
  - IRRAD (24 GeV p/beam)
- collected charge > **6000 e$^-$**.
- The sensors must withstand **1000 V** without breakdown after **non uniform** irradiation.
- Measure efficiency and resolution after irradiation.

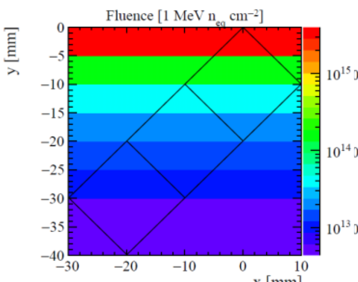
IRRAD @ CERN
24 GeV protons

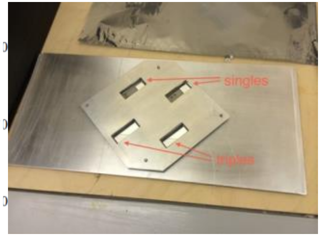
Reconstructed profile





setup



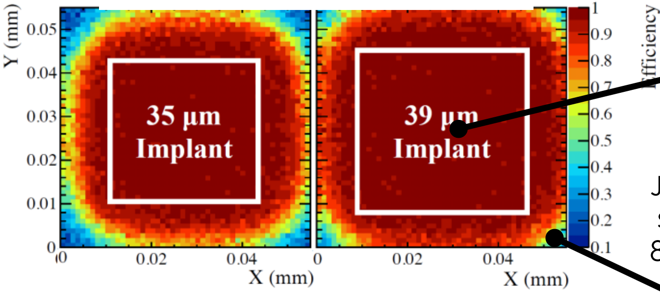


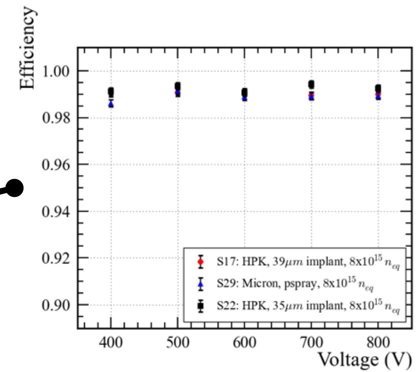
Irradiation profile

KIT @ Karlsruhe 26 MeV p

Efficiencies

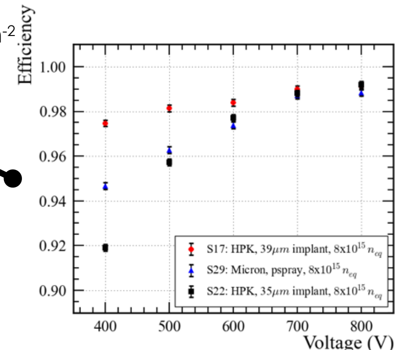
S22 S17 HPK 300V

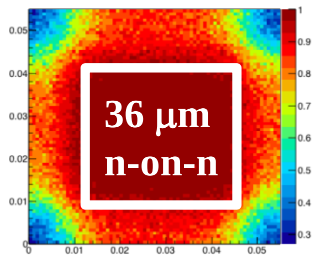




JSI irradiated sensors

8x10^{15} 1MeV n_{eq}.cm^{-2}





S27 Micron 300V

At 1000 V the corners are recovered.