LHCb Silicon Detector Upgrade

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IAS Program on High Energy Physics 2021

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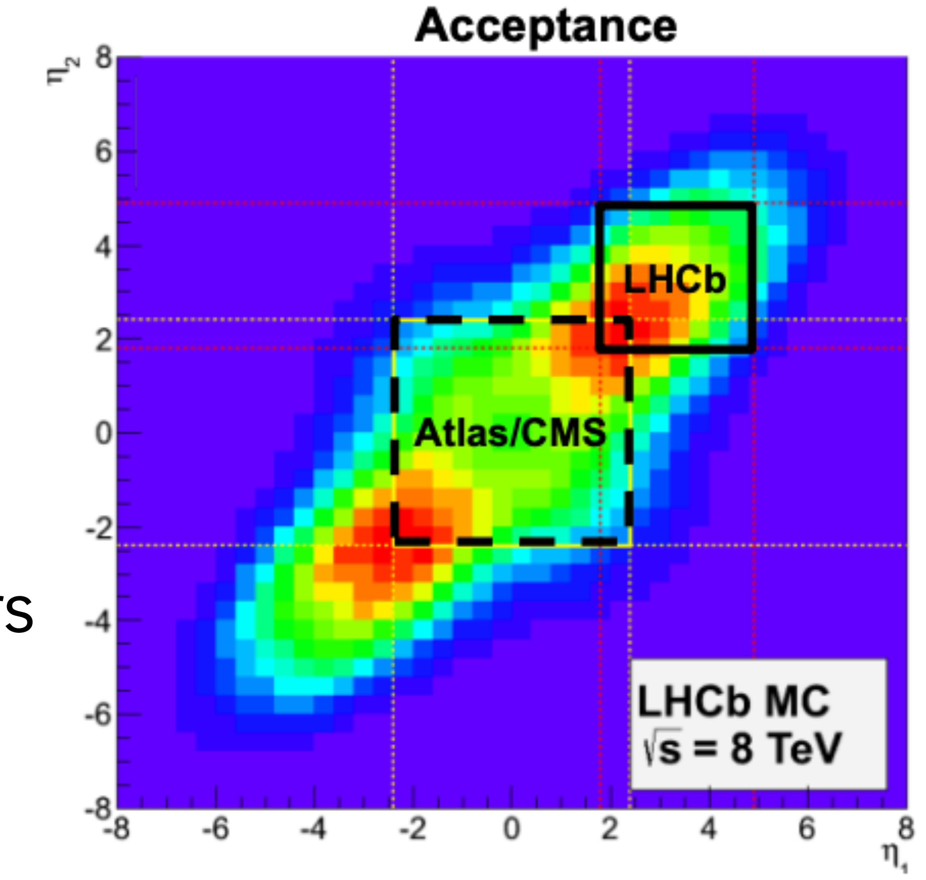
Outline

- LHCb Upgrade: motivation and schedule
- VErtex LOcator
- Upstream Tracker
- Future plans

LHCb detector and its upgrade

A Forward General-Purpose Detector at the LHC

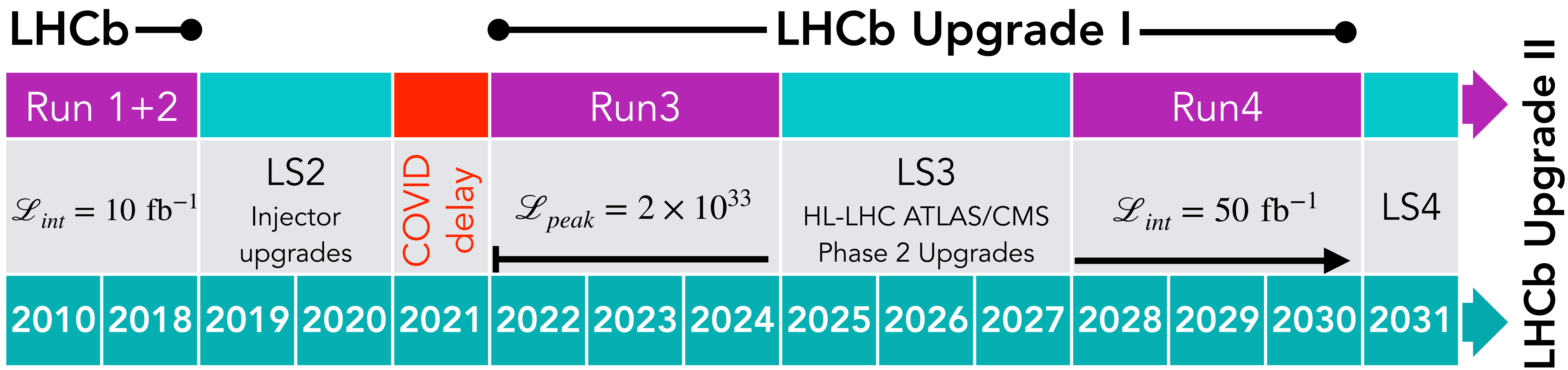
- Forward arm spectrometer with unique coverage in pseudorapidity ($2 < \eta < 5$)
- Catching 40% of heavy quark production cross-section in 4% of solid angle
- Precision measurements in beauty and charm sectors
- Extended physics program to QCD, EW, direct searches and participation in heavy ion runs



Why upgrading LHCb?

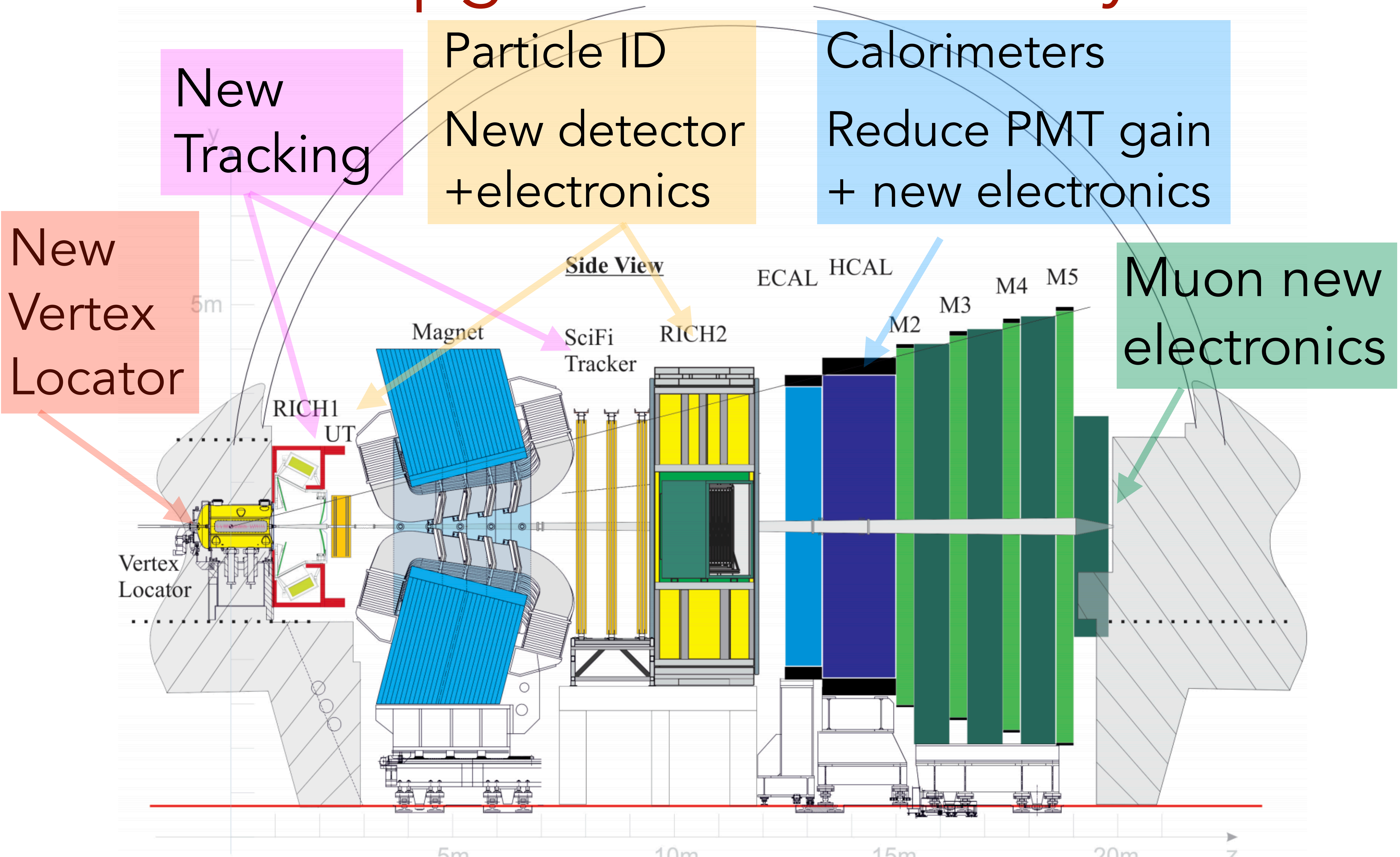
- Go beyond Flavour Physics: from exploration to precision studies
- No significant signs of New Physics in Run1 and 2 but anomalies observed!
  - R(D*), R(K), R(K*), etc
- Aiming for more precision:
  - BR($B_s \to \mu^+\mu^-$) down to ~10% of SM
  - CKM γ angle to ~1°
  - $2\beta_s$ to precision <20% of SM value
  - Charm CPV search below 10^{-4}

Upgrade overview



- **LHCb Upgrade I** is ongoing (LS2), almost a new detector for Run3 and Run4
  - Full software trigger and all detectors readout at 40MHz
  - Replace tracking detectors + PID + VELO to face $\mathcal{L}$ ~ 2 x 10^{33} sec^{-1} cm^{-2}
  - Consolidate PID, tracking and ECAL during LS3
- **LHCb Upgrade II** will start on LS4 and run beyond Run4
  - Use new detector technologies + timing to increase $\mathcal{L}$ ~ 1.5 x 10^{34} sec^{-1} cm^{-2}

LHCb Upgrade I detector layout

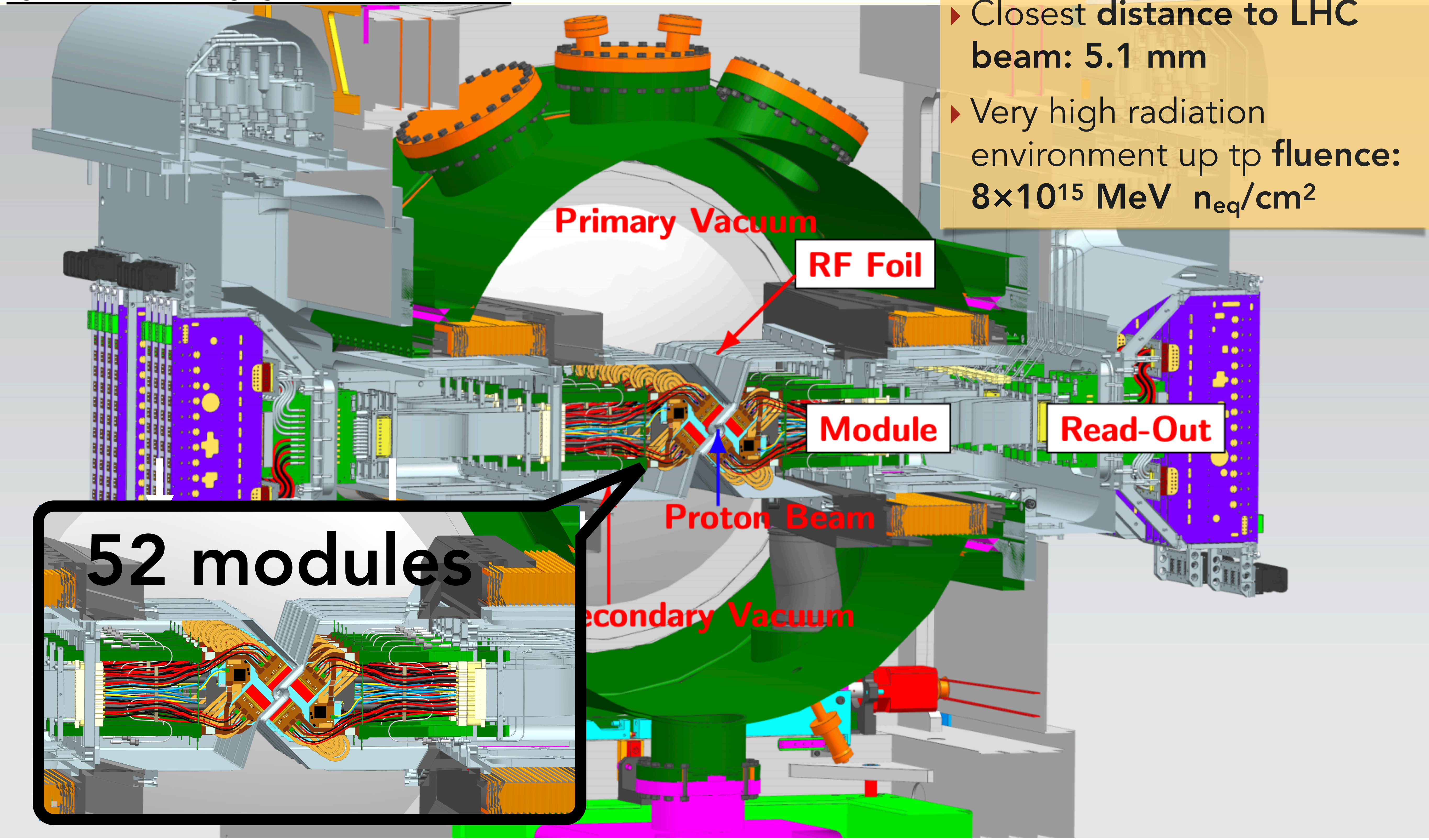


Trigger-less readout & SW trigger on GPUs

Overview of the new VELO

CERN-LHCC-2013-021

- Closest **distance to LHC beam: 5.1 mm**
- Very high radiation environment up tp **fluence: 8×10^{15} MeV n_{eq}/cm^2**



The RF Foil

Motivations

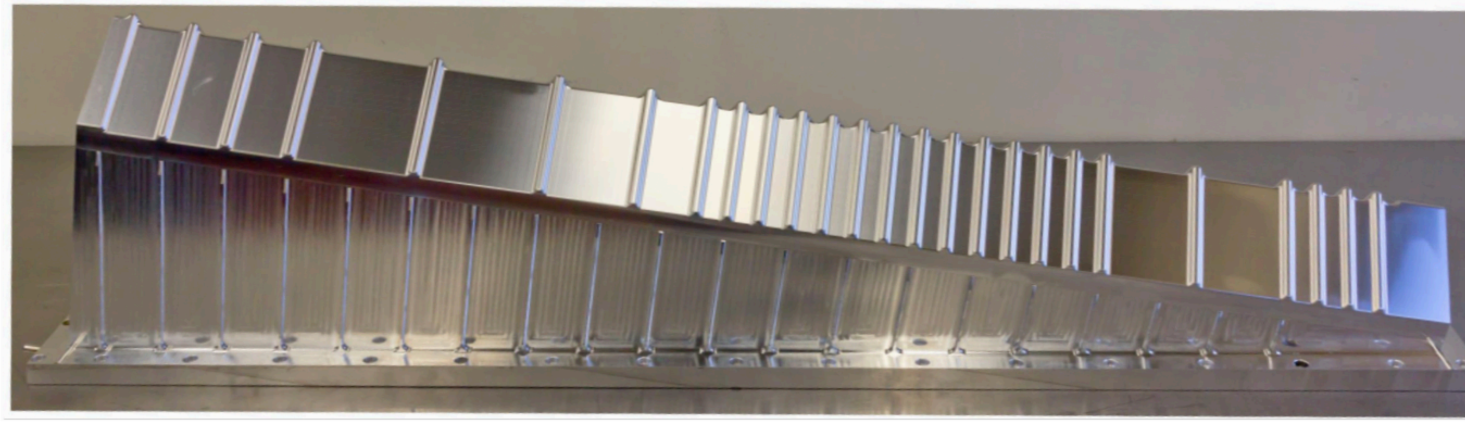
- Separate primary and secondary vacua (contamination from outgassing)
- Guide beam wakefields
- RF shielding of electronic components

Specifications

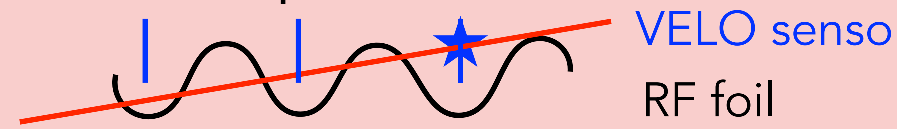
- Reduced material budget
- Withstand 10 mbar pressure difference
- 3.5 mm clearance from the beam and 900 μm clearance from the sensors
- Dimensions: 1.1 m × 0.2 m × 0.4 m

Engineering Marvel

- Start from a solid forged Al alloy block
- >98% of material is milled away: 6 months
- Final thickness at tips of modules: ~250 μm

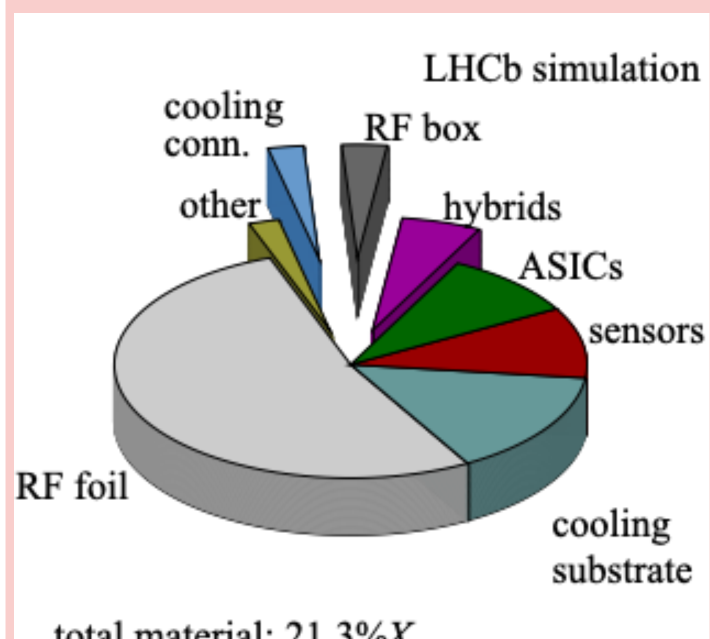


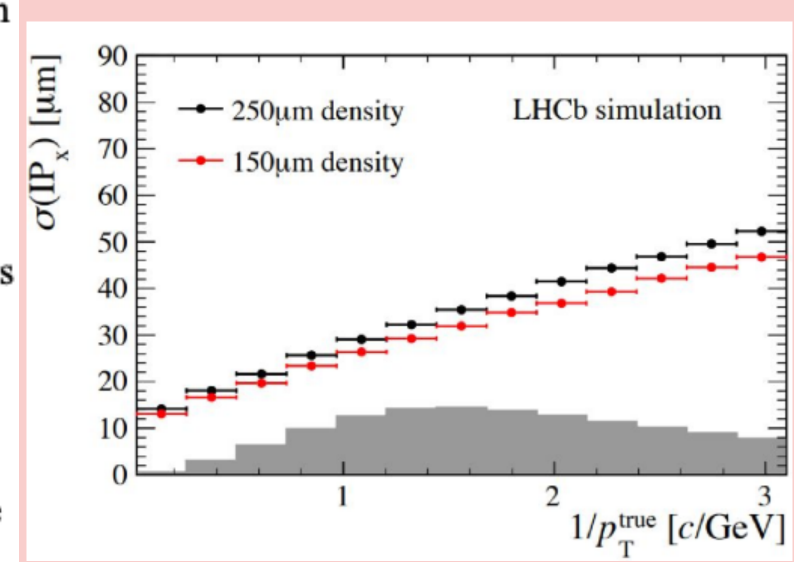
Foil has a corrugated shape: clearance from modules



Particles traverse corrugate part multiple times before first measuring point

Improvement of 10% on key physics parameters when reducing thickness from 250μm to **150μm**

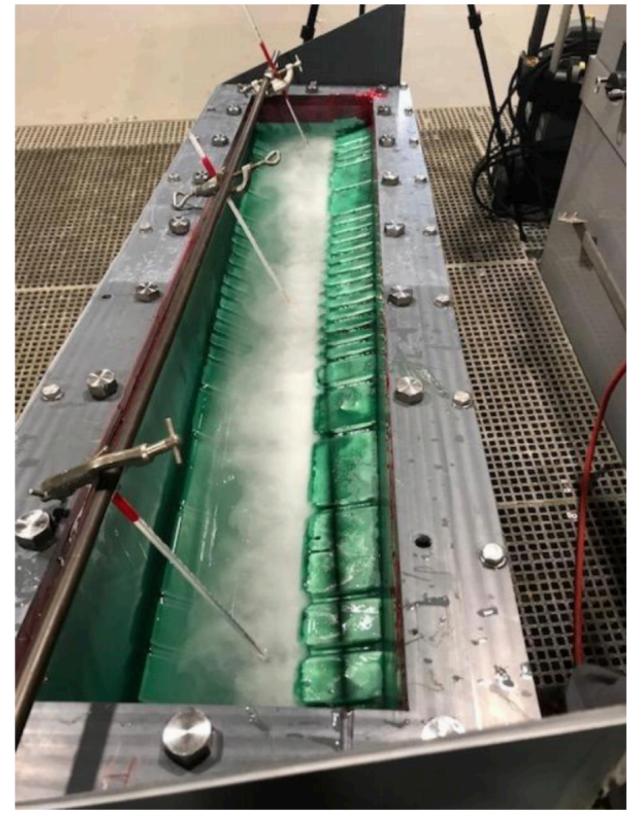




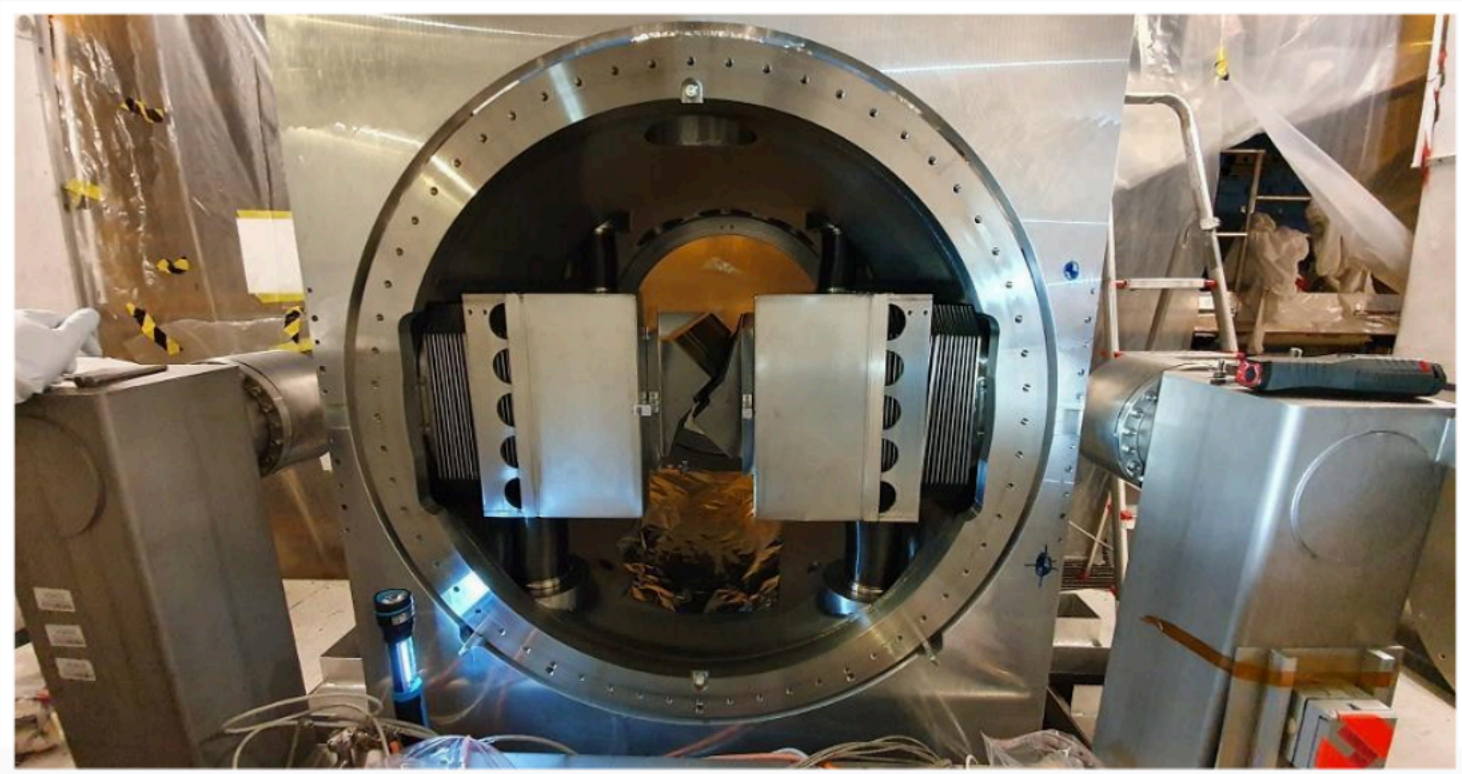
The RF Foil: etching

Etching

- Chemical etching with NaOH solution (only innermost region)
- Procedure well controlled and performed in steps
- Bonus challenge: thickness variations from milling
- Extensive metrology campaign to create a mask
- Procedure demonstrated on path finder prototype box



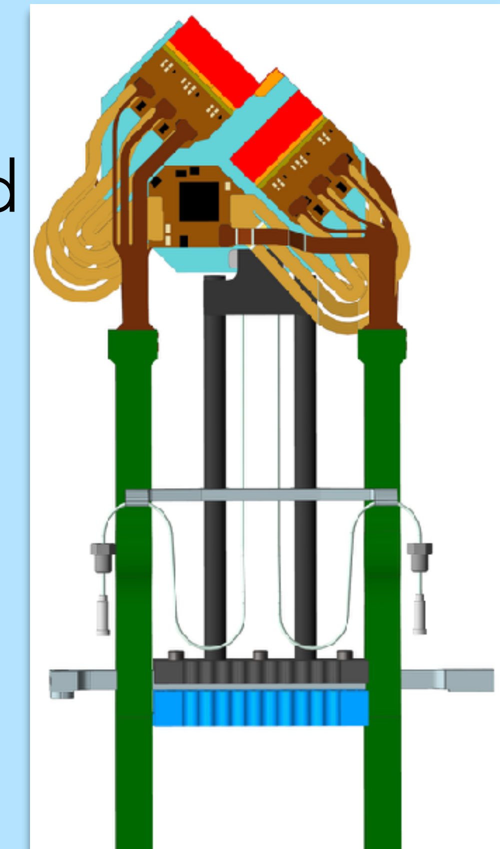
RF foil installation performed after the first COVID CERN lockdown

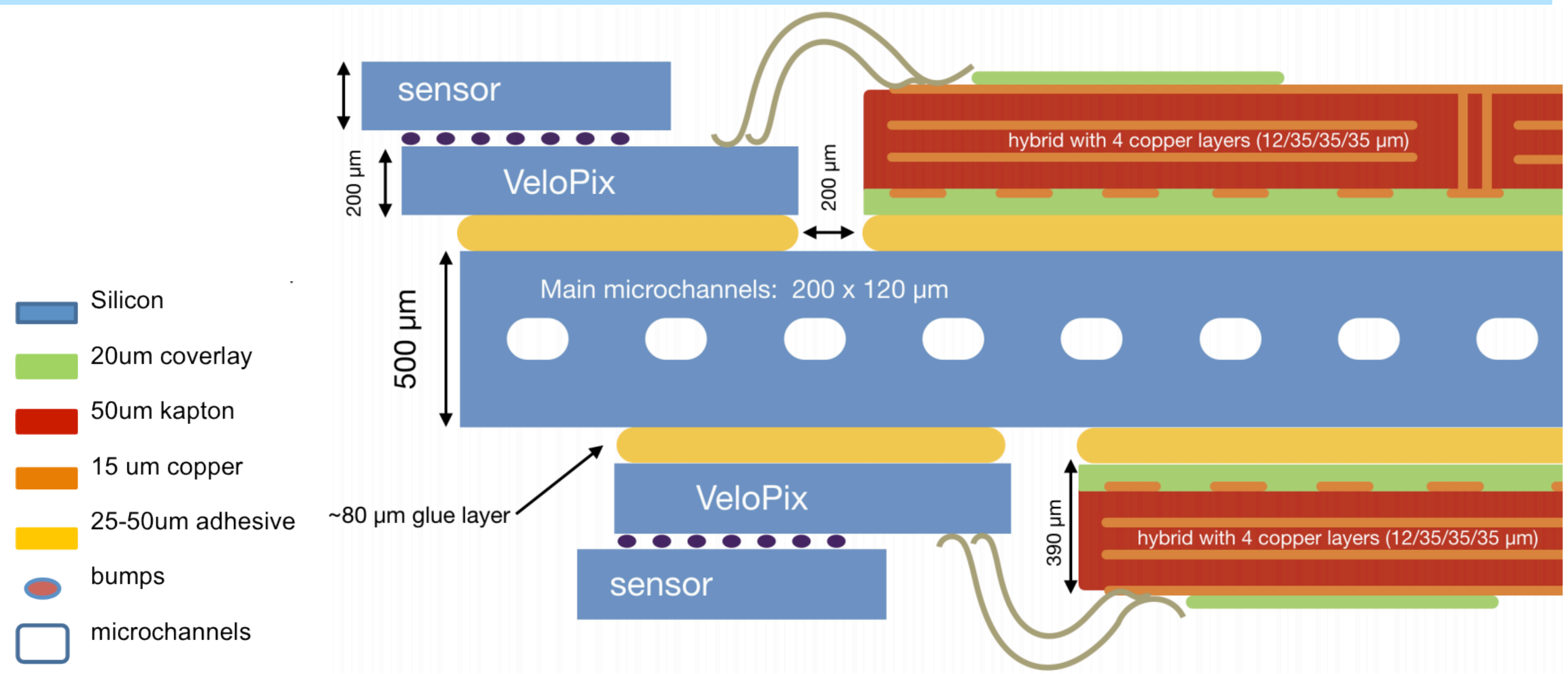


VELO

- Silicon pixel modules around the LHC beam interaction region
- LHCb has trigger-less readout - full detector readout @ 40 MHz
- Cooling requirement
  - CO_2 cooling
  - Sensor tip temperature <**-20°C**
    - Power dissipation per module ~30W
  - Operating in **vacuum**
  - Low material: 5mm of the silicon sensor are not glued on the cooling substrate (innermost part)

- Four n-on-p sensors per double sided module
- Each sensor (43 x 15 mm) bonded to three VeloPix ASIC's: 55 μm
- Detector Active area = 0.12 m^2
- 2 GBTx for signal fan-out to VeloPix
- 2 bidirectional slow control links
- 20 unidirectional high speed data links





VELO

- Silicon pixel modules around the LHC beam interaction

➡**Solution**: **Evaporative CO_2 cooling through microchannels etched in silicon**

- Excellent thermal efficiency
- No thermal expansion mismatch with silicon ASICs and sensors
- Radiation hardness of CO_2
- Very low contribution to the material budget

substrate (innermost part)

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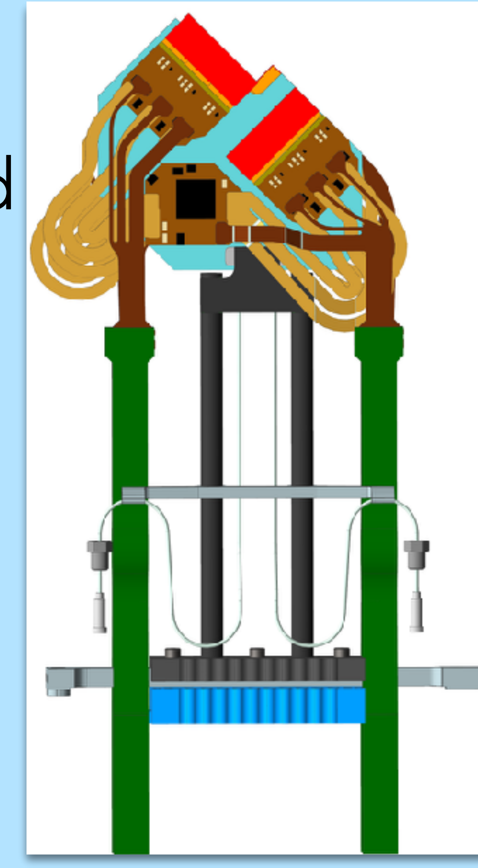
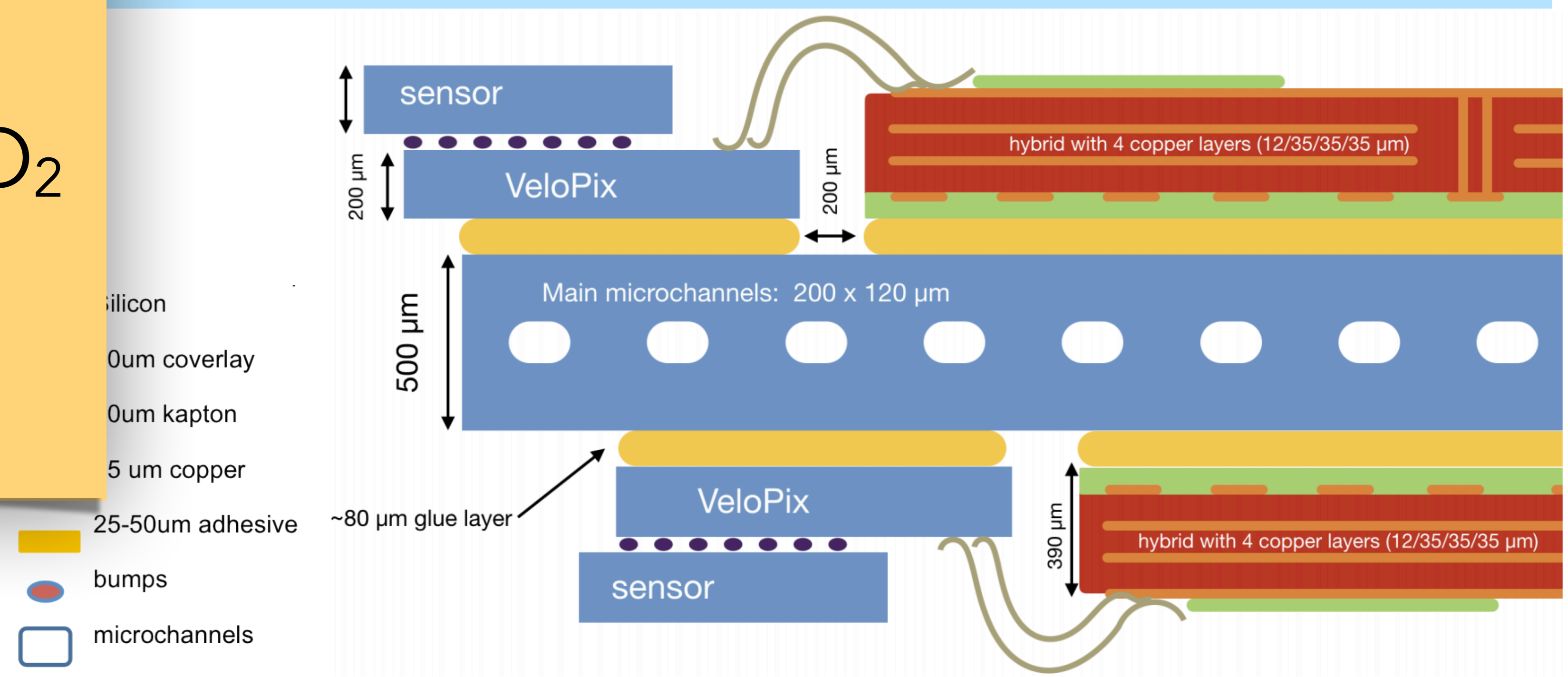
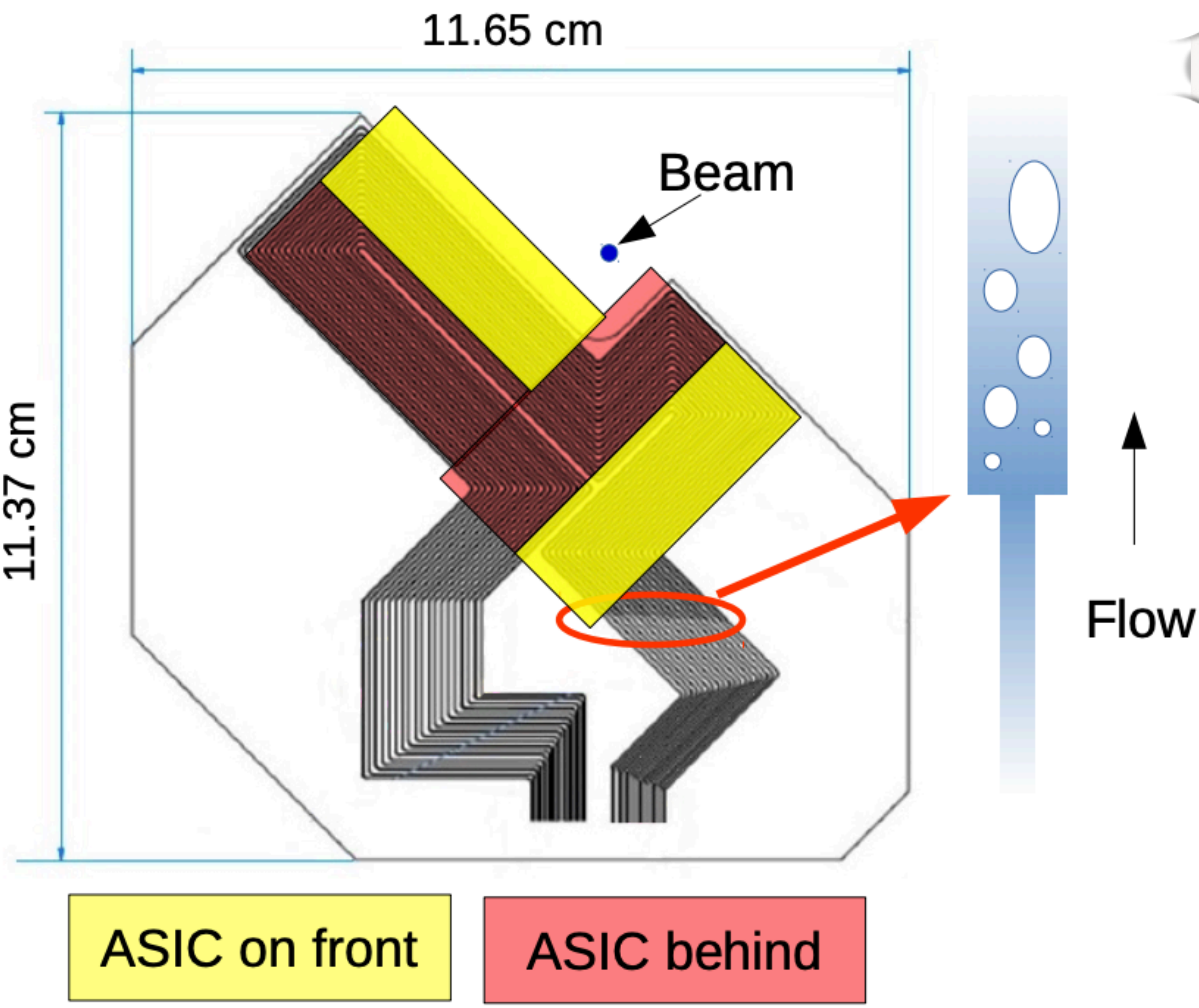




Micro-channel cooling



Increase in cross-section between the restriction and the main channels triggers the boiling

500 μm thick silicon substrate

Input restrictions:

- 60 x 60 μm , 40 mm long
- Dominant pressure drop
- Prevent instabilities among the channels

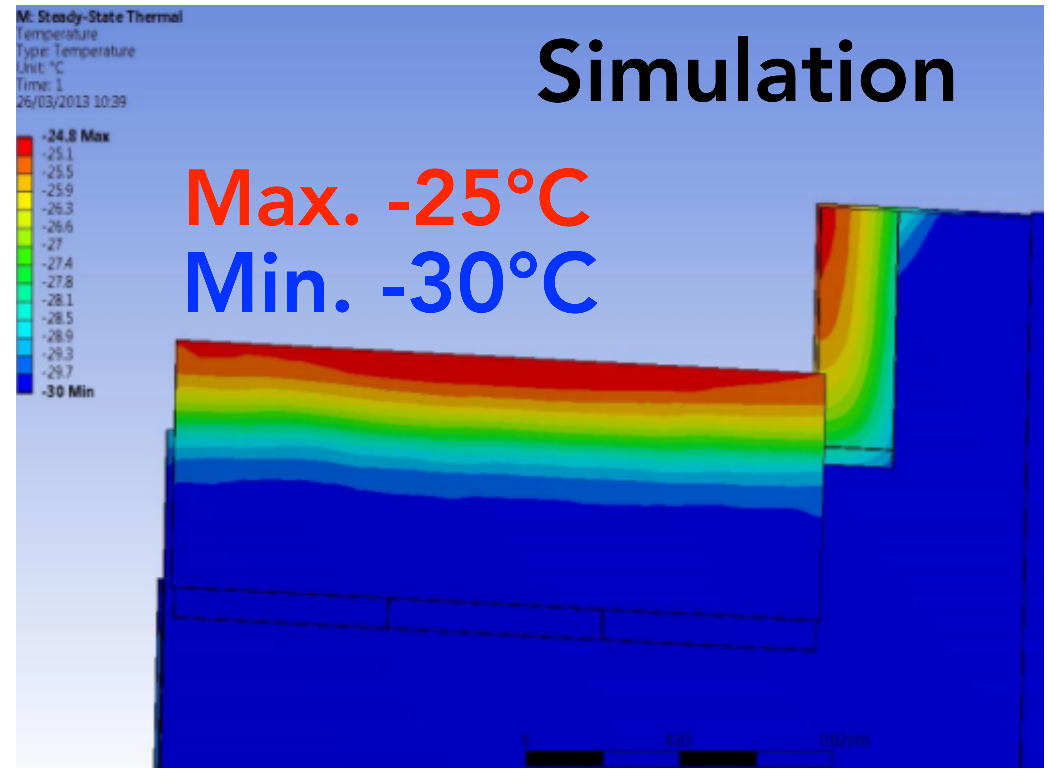
Main channels

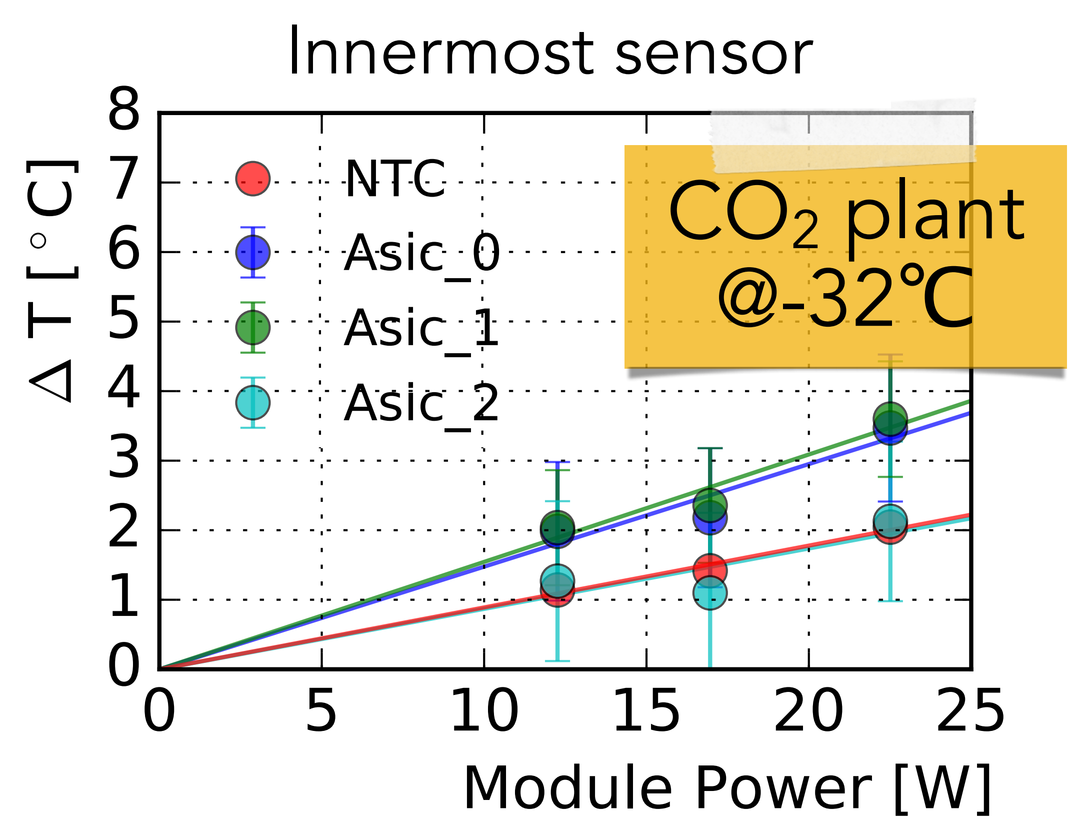
- 120 x 200 μm
- [230, 290] mm long
- Heat is absorbed by the CO_2: change in gas/liquid ratio

Cooling performance

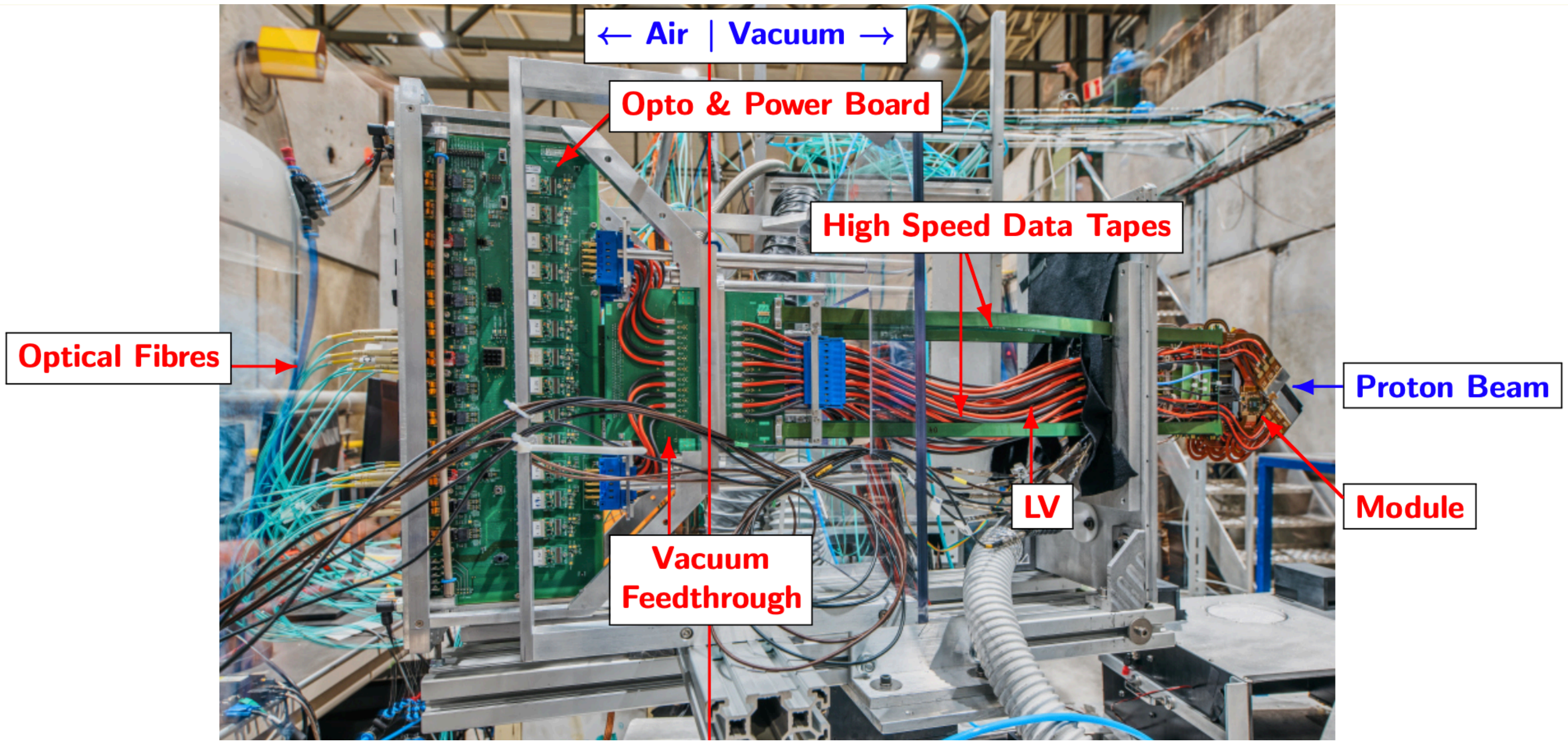
Cooling performance has been evaluated using thermal mockups emulating half pixel module

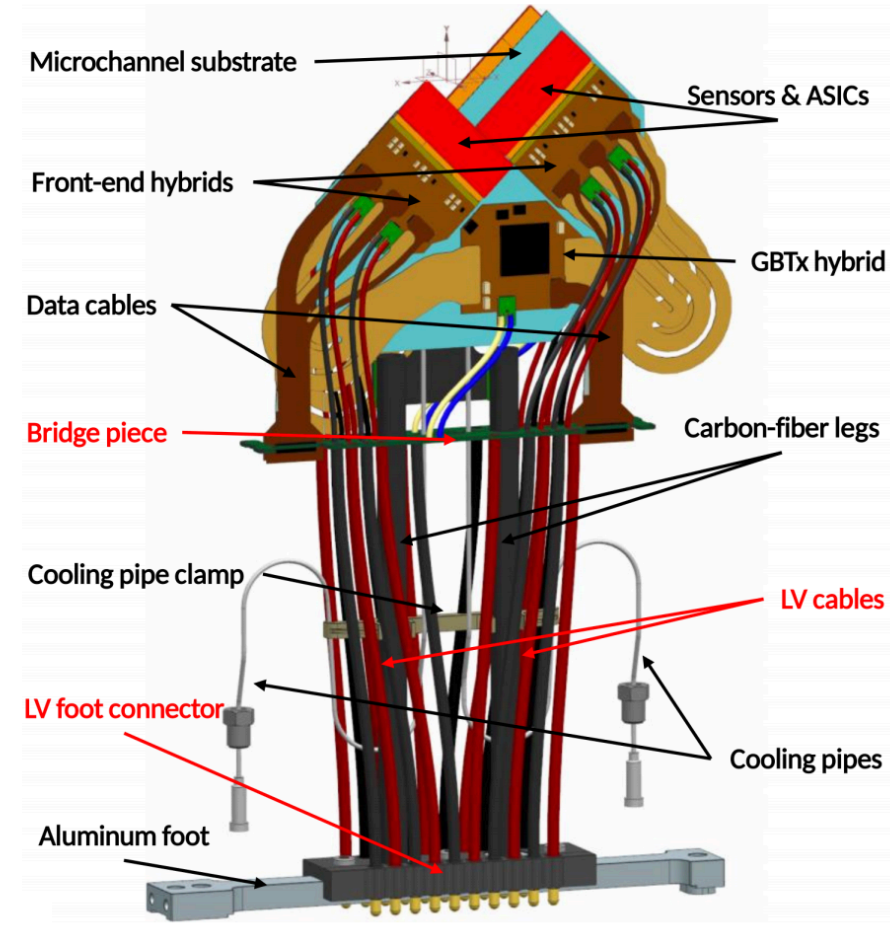
- Test performed with ASIC heaters at 20 W gives a ΔT~ 6℃
  - Effectiveness of the substrate at providing local cooling
  - ASIC power is concentrated at the part more remote from the silicon tip
- **Full module** power consumption ~**23 W**
  - Expected end-of-lifetime power dissipation on the sensor ~1W: **27W**
- To reduce material innermost part of the sensor is not in contact with the cooling substrate
  - **Overhang power~1.6W**





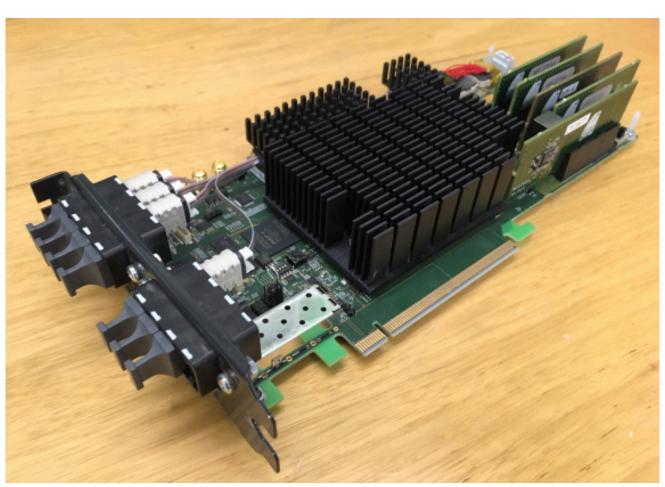
Readout chain





PCIe40 Read-Out Card

- Common off-detector hardware
- Two firmware flavours
- Slow Control: 1 card per 13 Modules
- High Speed DAQ: 1 card per Module

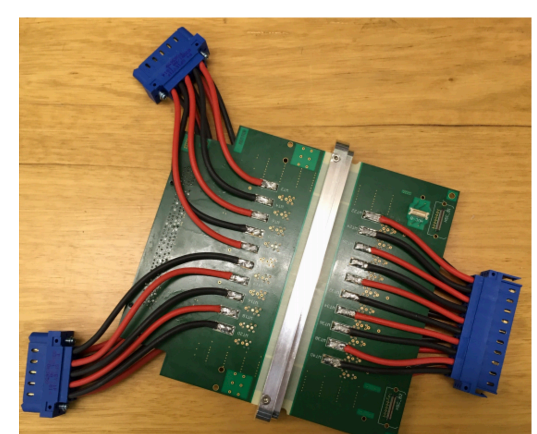


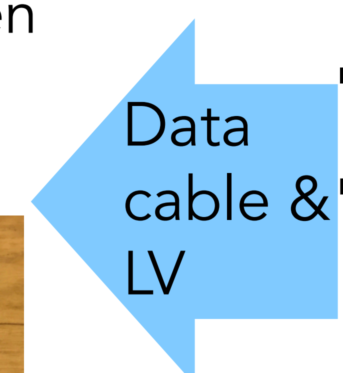
Opto- & Power Board (OPB)

- Low voltage to all components in read-out chain
  - Radiation hard FEASTMP DC/DC converters
- Electrical ↔ Optical signal convertors: VTTx/VTRx
- Controlled via GBTx and SCA

Vacuum Feedthrough Board (VFB)

- Transmit control & high speed signals, temperature monitoring, LV and HV between Module and OPB

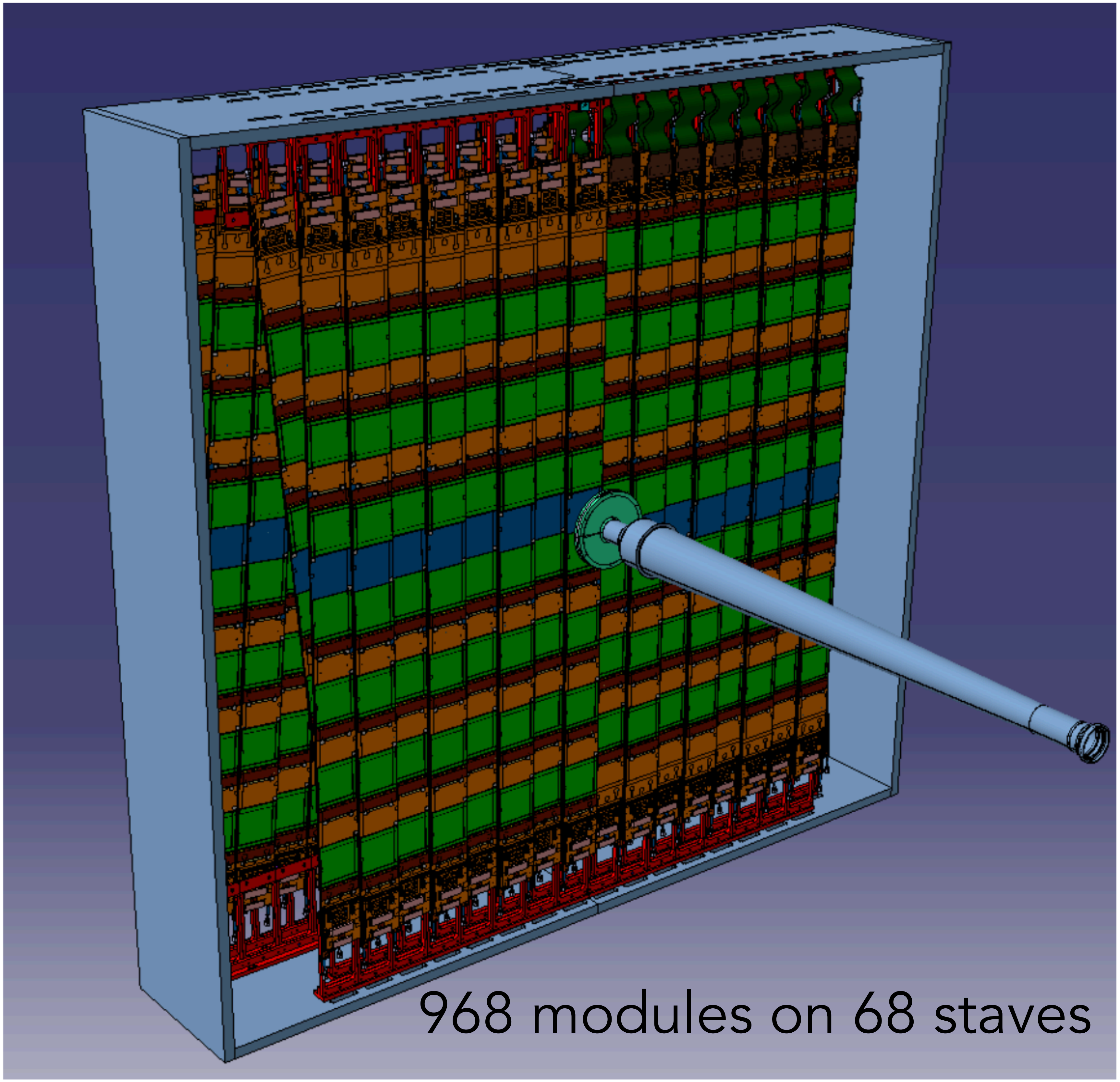




Module

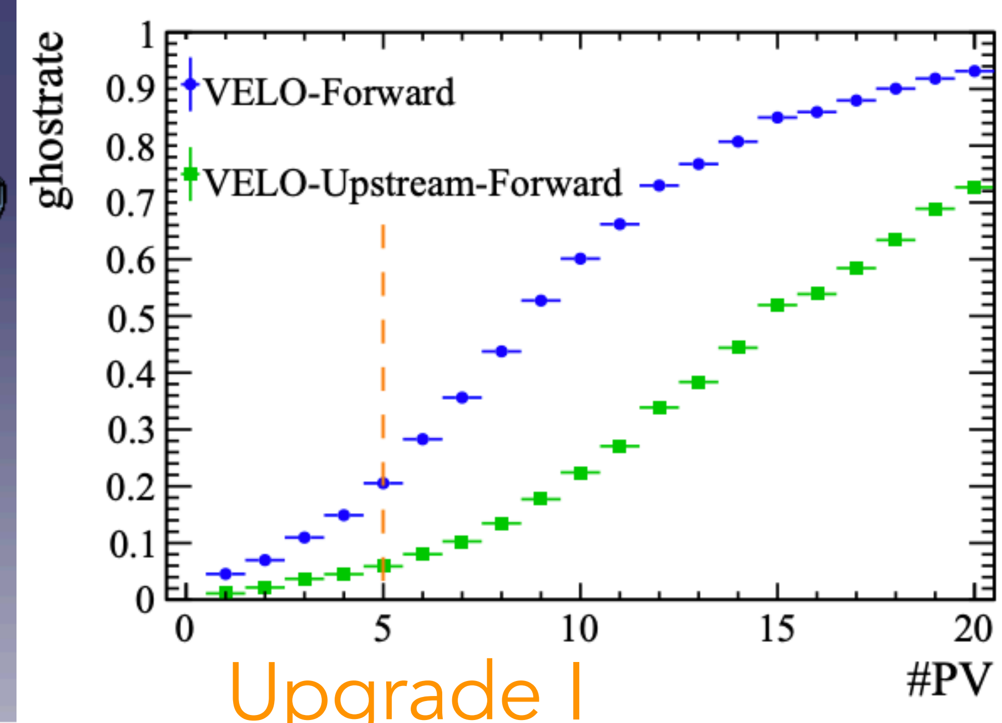
Upstream tracker

CERN-LHCC-2014-001

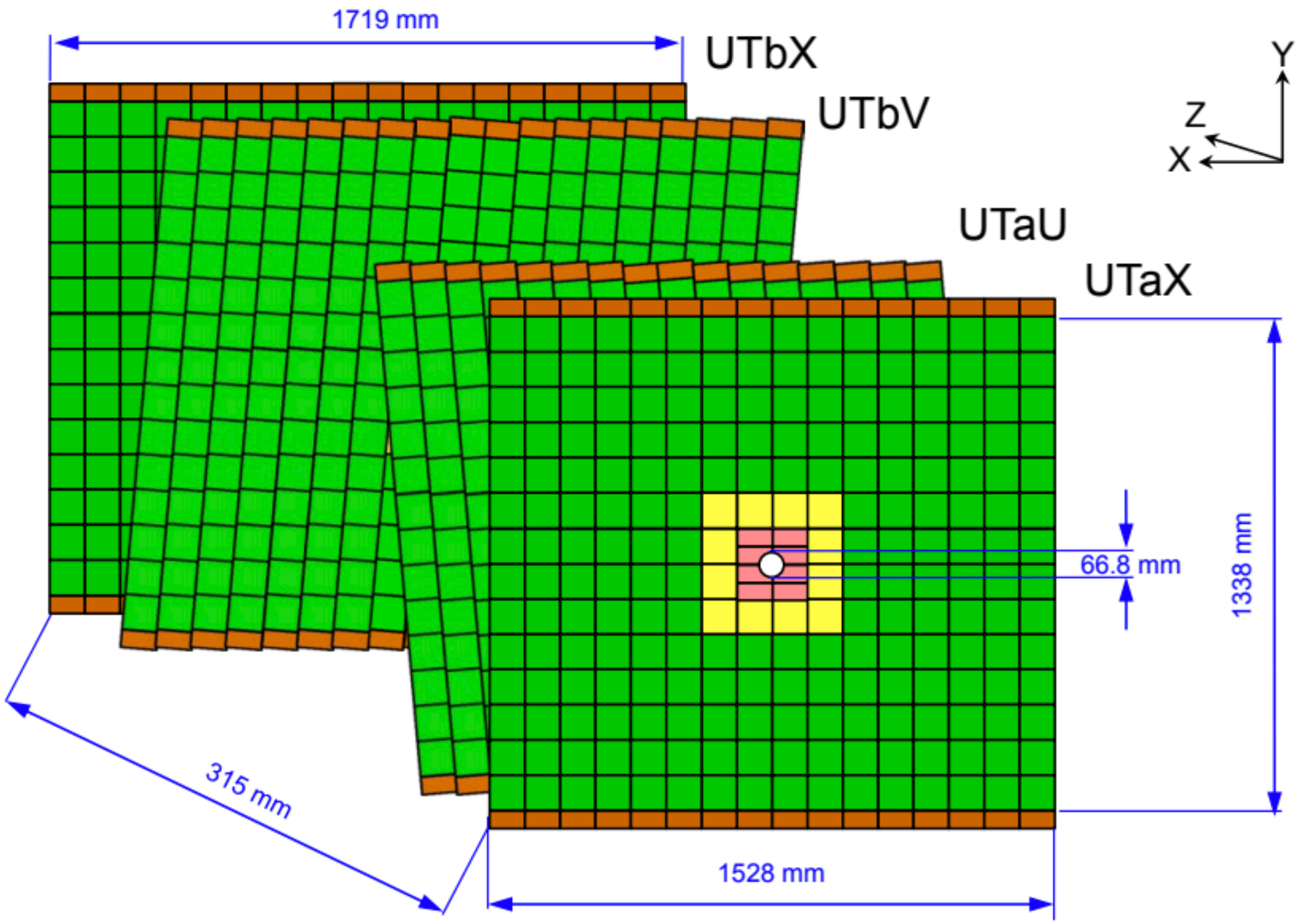


Scope

- Improve p_T resolution and suppress ghost tracks
- Trigger speed up: using Velo+UT matching, very low-pT tracks can be removed (pT < 0.4 GeV) and search window in SciFi tightened



UT design and characteristics



Silicon micro-strip detector

- Four layers (x, u, v, x) upstream of magnet: 2 m^2 each
  - Two planes with vertical strips, two rotated by ±5°
- Finer granularity and closer to beam

Sensor	Type	Pitch	Length	Strips	# Sensor	Shape
A	p-in-n	187.5 µm	99.5 mm	512	888	Square
B	n-in-p	93.5 µm	99.5 mm	1024	48	Square
C	n-in-p	93.5 µm	50 mm	1024	16	Rectangle
D	n-in-p	93.5 µm	50 mm	1024	16	Circular cut-off

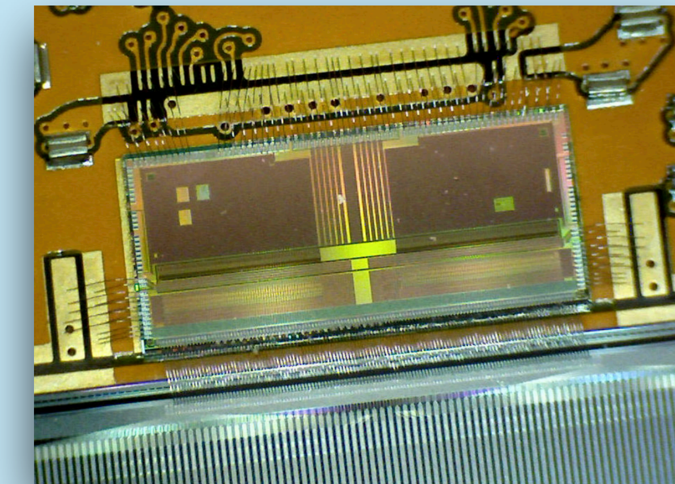
Sensor Features

- In the inner-most region finer segmentation and radiation hardness
- A-type sensors: embedded pitch adapters (fan-up)
- Top-side HV biasing
- Cut off around beam pipe

UT: readout & mechanics

Readout ASIC: SALT (4192 chips)

- 128 channels with 6-bit ADC (5 bit and polarity)
  - 130 nm-TSMC with 30 MRad radiation tolerance
- 40 MHz readout
- Fast shaping time/return to baseline
- Pedestal & common mode subtraction, zero-suppression

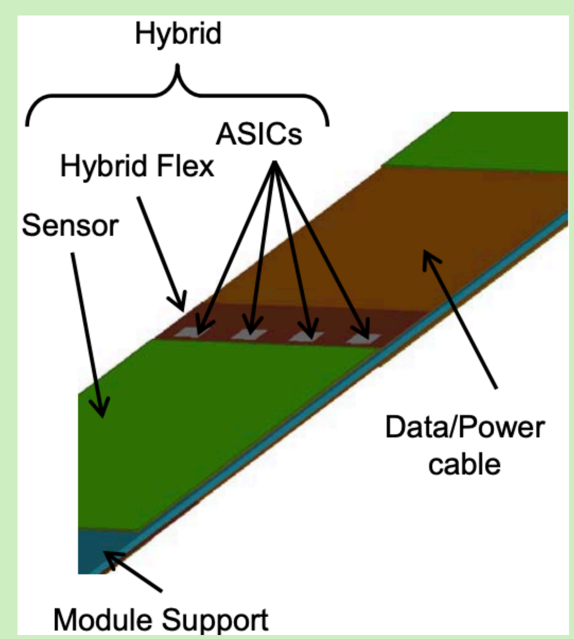


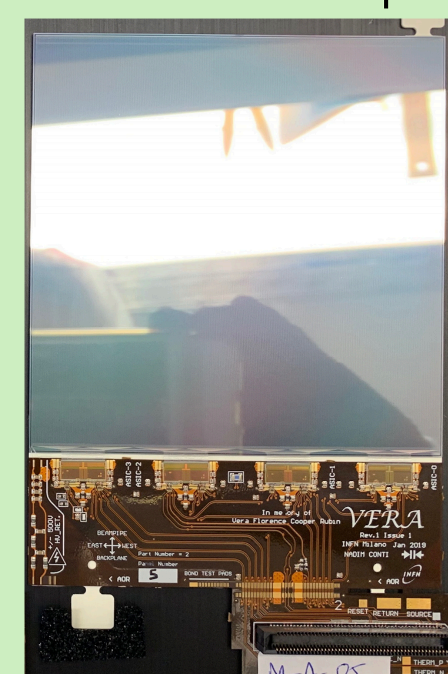
Peripheral electronics

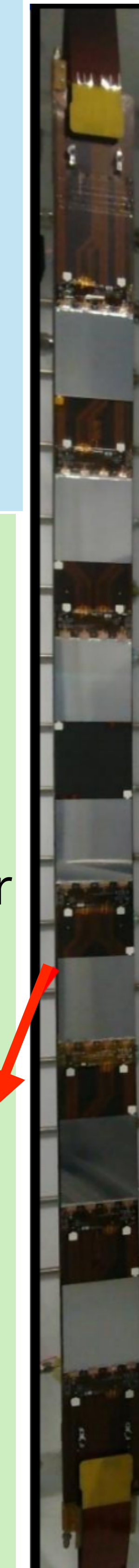
- A flexible pigtail cable connects the stave to PEPI
- Backplane distributes balanced load to DCBs
- DCBs optically send data to LHCb DAQ
- Bandwidth~ **7.1 Tb/s**
- Also control system via VTRx

Stave

- 1.6 m x 10 cm low-mass support
- Integrated Ti pipe for Bi-phase CO_2 cooling
- Low-mass Kapton flex for readout, power and grounding
- Sensors on front and back face overlap







What's next? Upgrade II

VELO

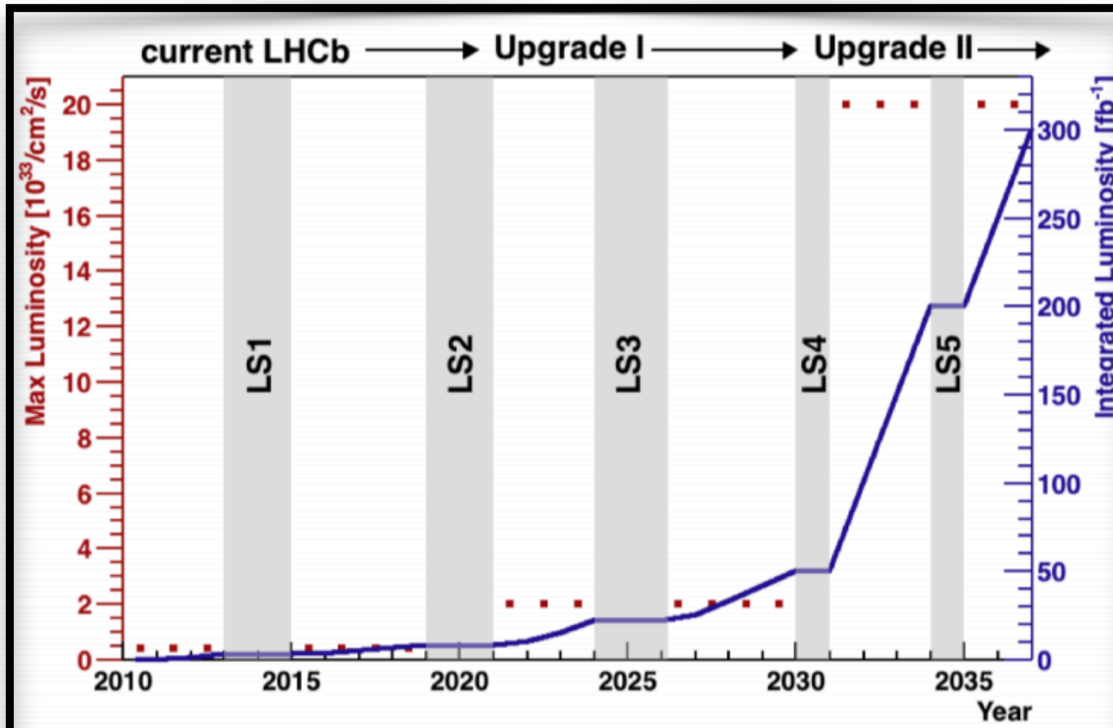
- Timing at high lumi is essential to keep the same performance as Upgrade I
- 4D tracking vs. timing layer is subject to further studies
- Main challenges: radiation, cooling, spacial resolution, data rate..
- R&D phase: several technologies are explored

UT

- UT staves, which were designed for UI, have insufficient bandwidth for event data
- Various scenarios on the tables, combination of current sensor and CMOS pixel sensor

Mighty

- Tracking would benefit by high granularity in the inner region
- Combine SciFi and CMOS technologies
- Upgrade Ib – 2 SciFi modules/layer, 4m^2 CMOS
- Upgrade II modification – New SciFi and 18m^2 CMOS



HL-LHC will deliver to LHCb a luminosity 1.5×10^{34} cm^{-2} s^{-1} →7.5 x Upgrade I…

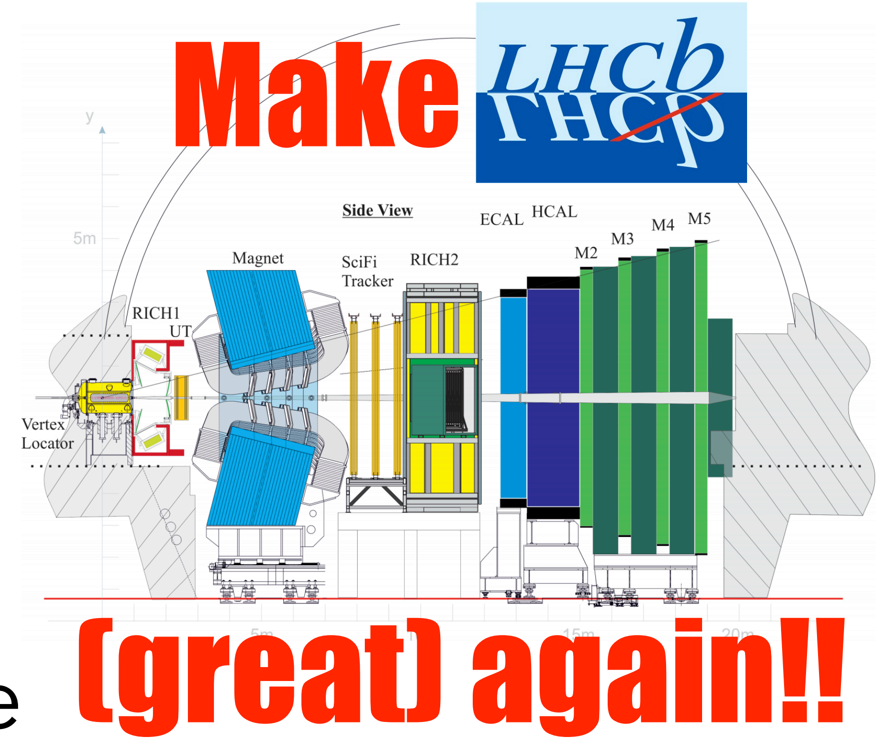
But also:

- 7.5 x multiplicity, data rates and track density
- 7.5 x radiation damage!!!

Conclusion

Upgrade I is on-going

- Significant progress made in the past month despite the COVID
- Schedule redefinition mandatory to face country restriction
- But … a great detector will be deliver in time for next exiting phase of LHCb data-taking



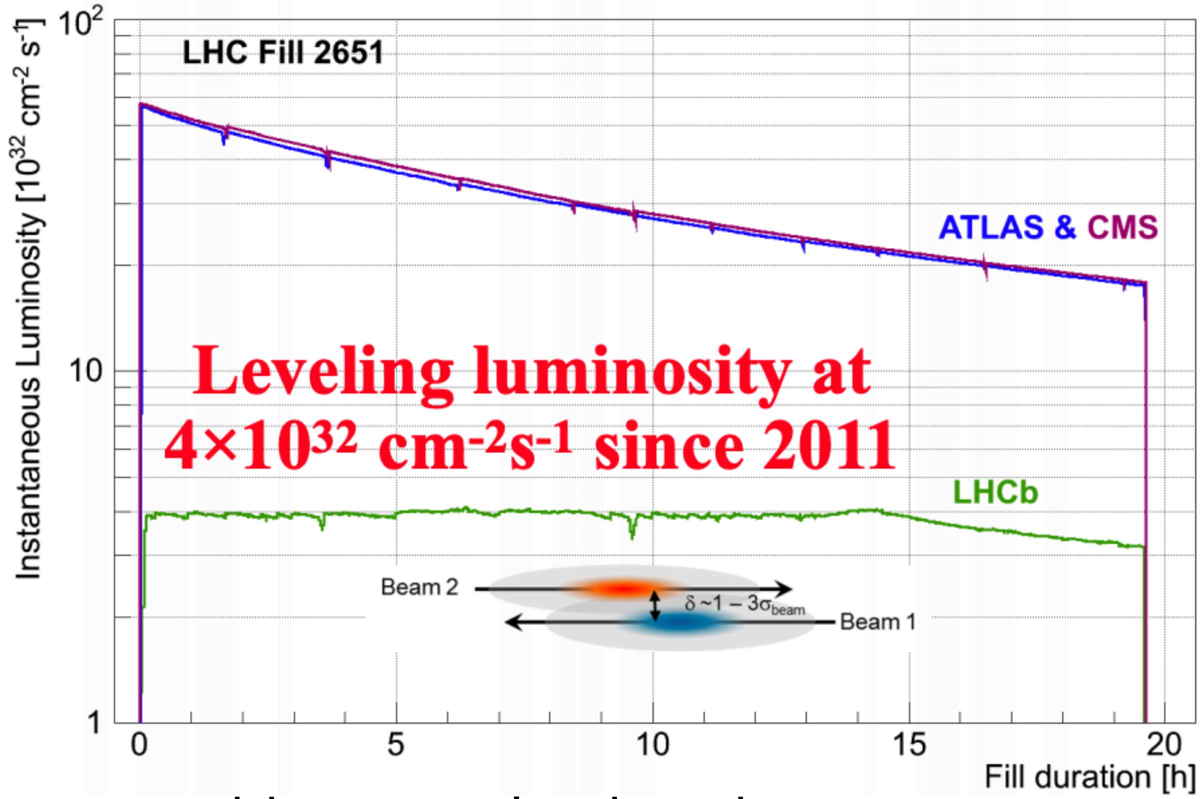
Upgrade II R&D is ramping up

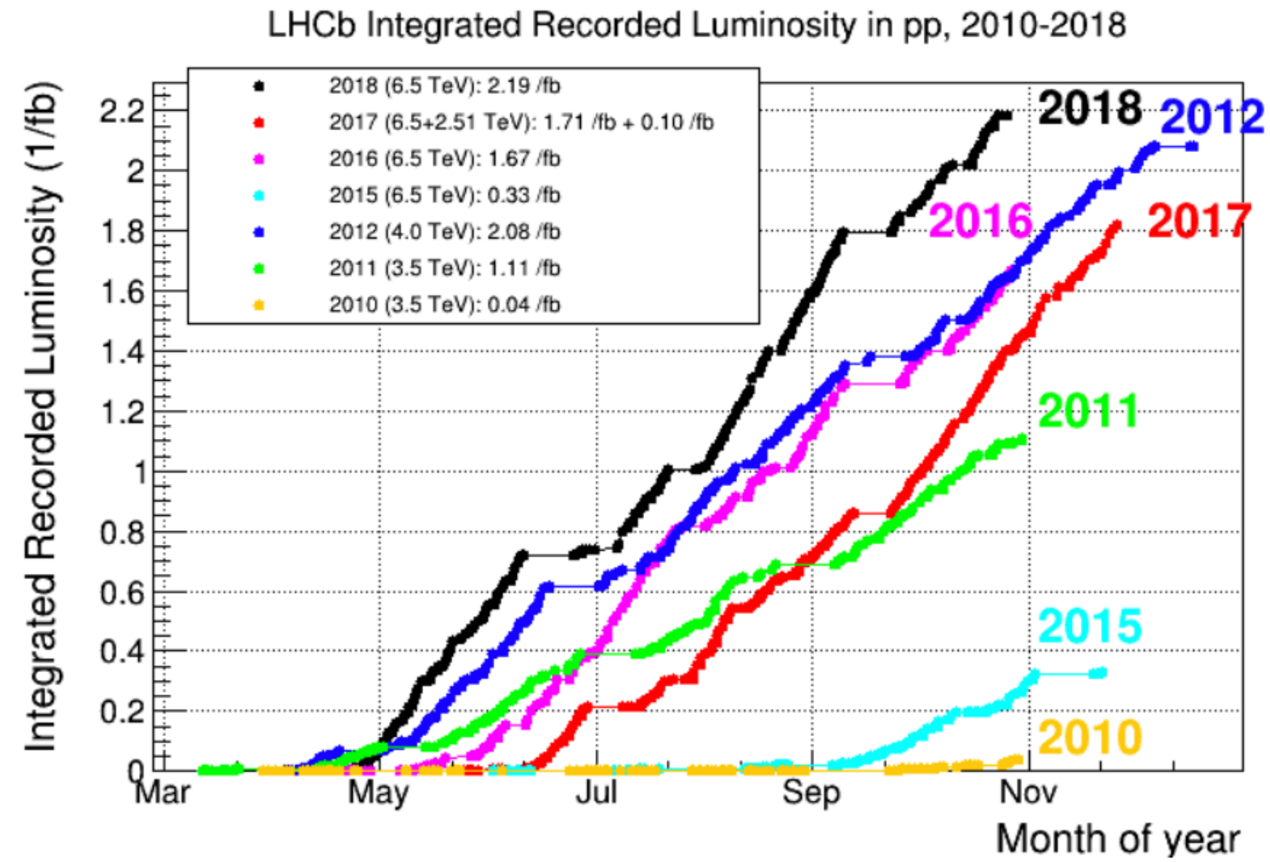
- R&D phase started
- Many options on the table
- It is time to explore new technologies and design the next masterpiece

Futuristic view of LHCb

Back up

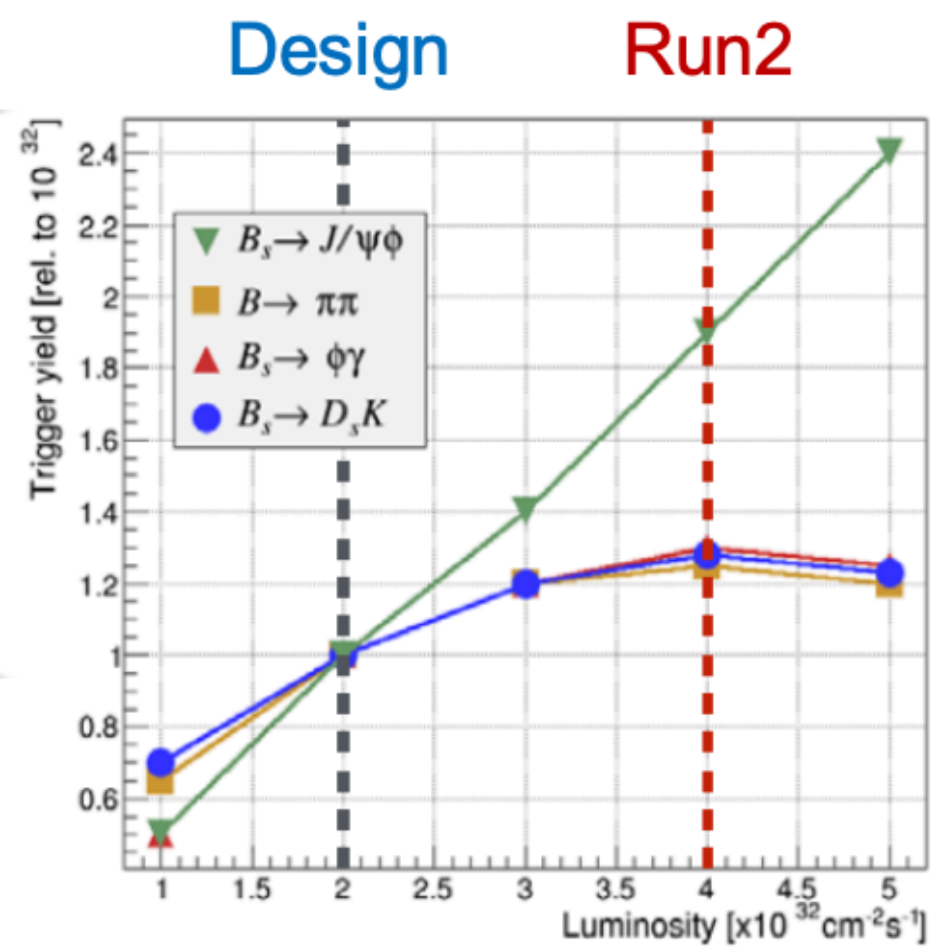
LHCb Limitation





- Limited by Level-0 hardware trigger
  - Maximum rate is 1.1 MHz.
- Higher luminosities:
  - Trigger yield saturates
  - Harder cuts on ET and pT
  - No real gain in statistics.
- Higher occupancy
  - Degraded detector performance.
  - Radiation damage of detectors.

Upgrade I will remove these constraints

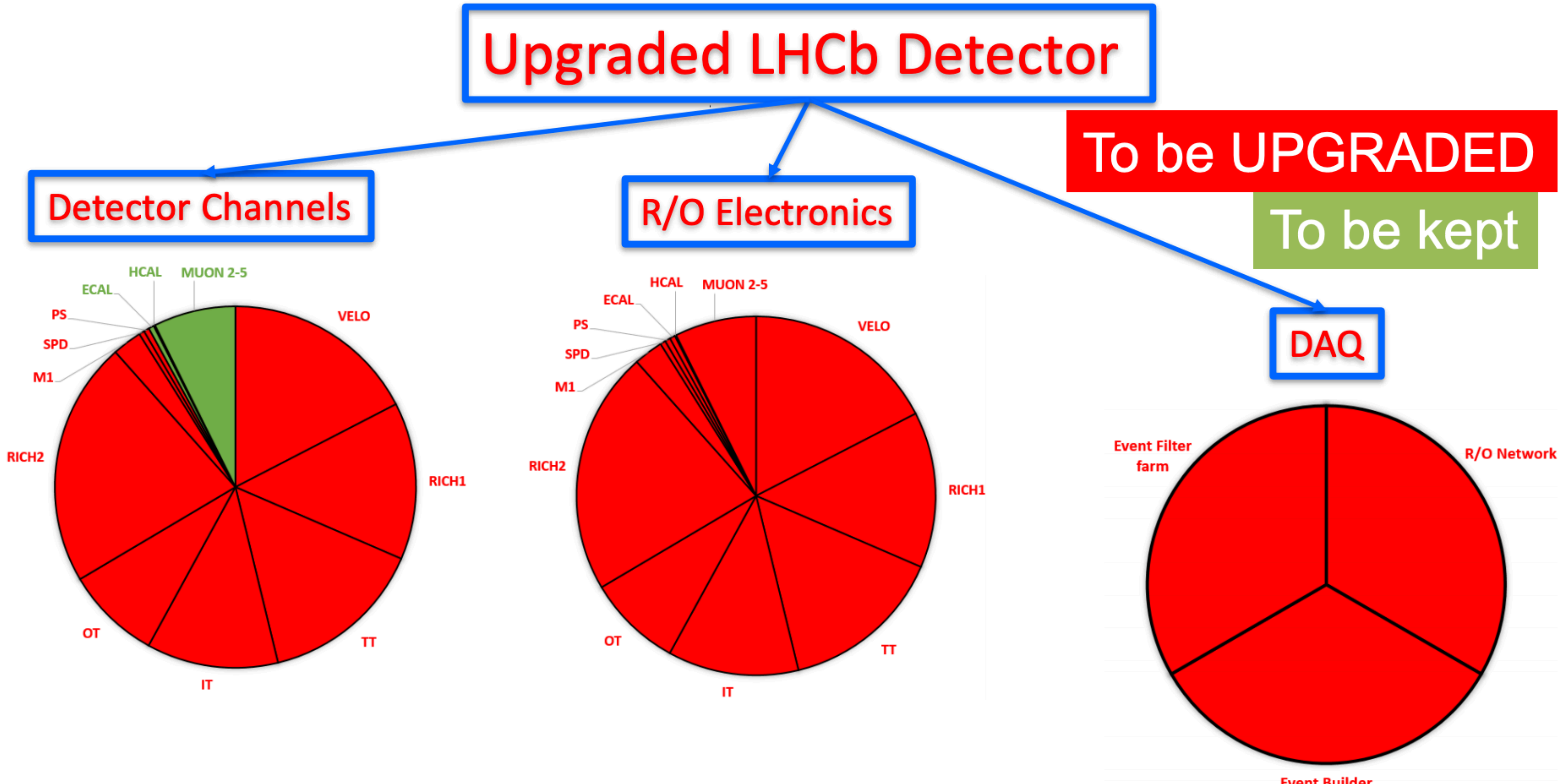


Performance table

arxiv.1808.08865

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert / \lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$B_s^0, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$b \to c\ell^-\bar{\nu}_l$ LUV studies					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

Phase-I Upgrade for Run 3

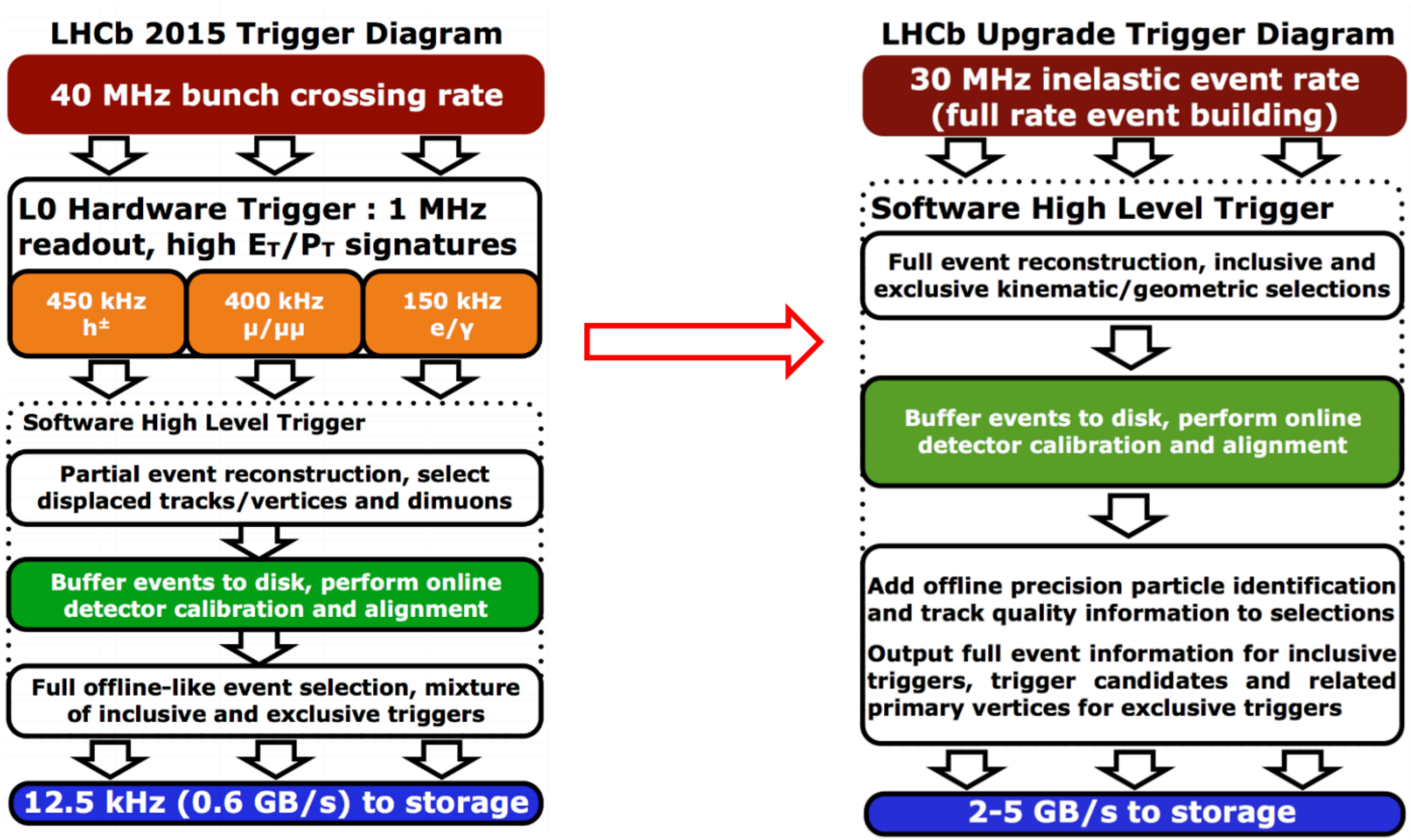


Major upgrade → it's a new detector all together!

LHCb Upgrade-I challenges

Remove L0 trigger!!

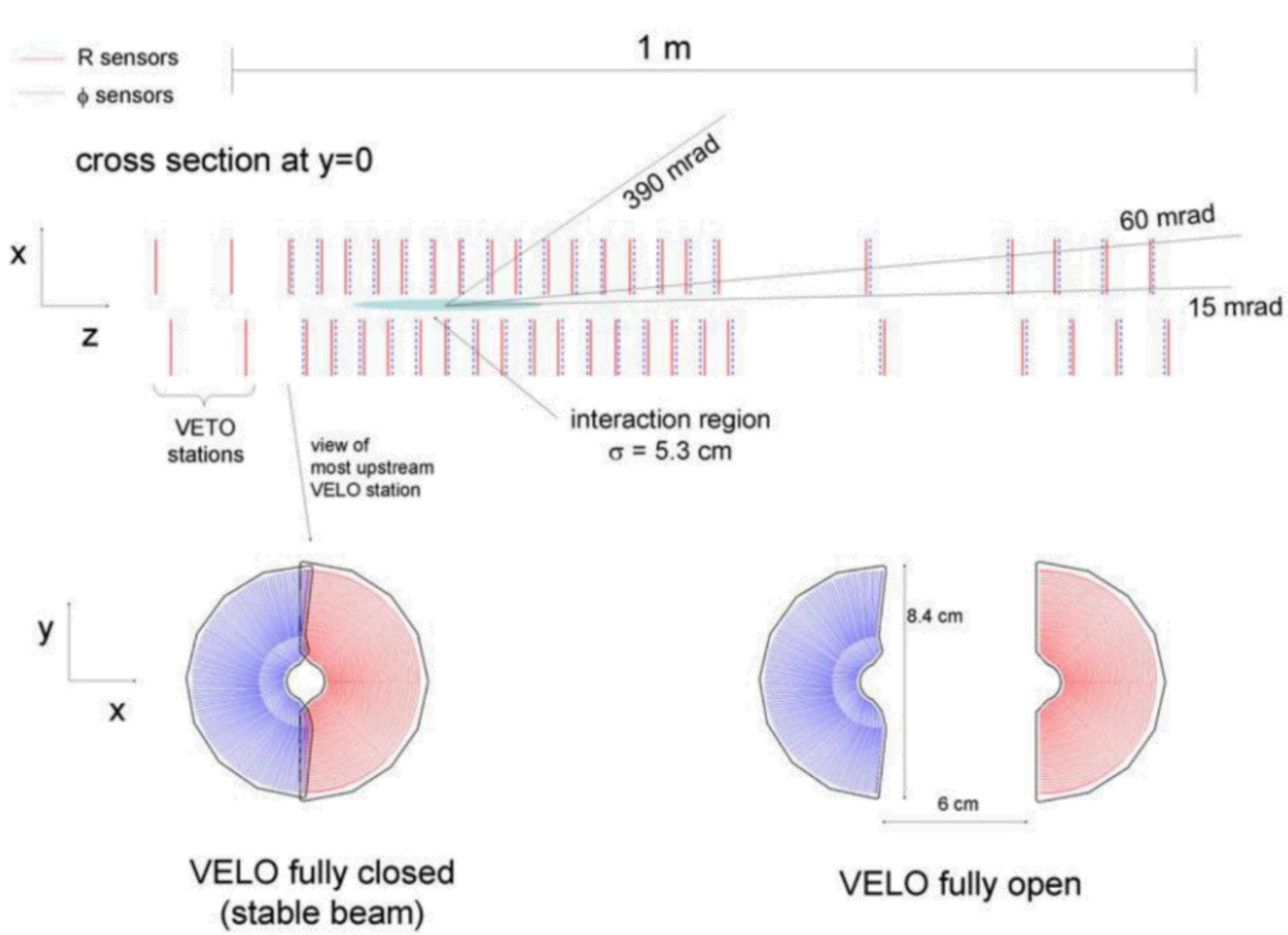
Achieved same reconstruction performance in harsher environment
Record all bunch crossings with fully software trigger

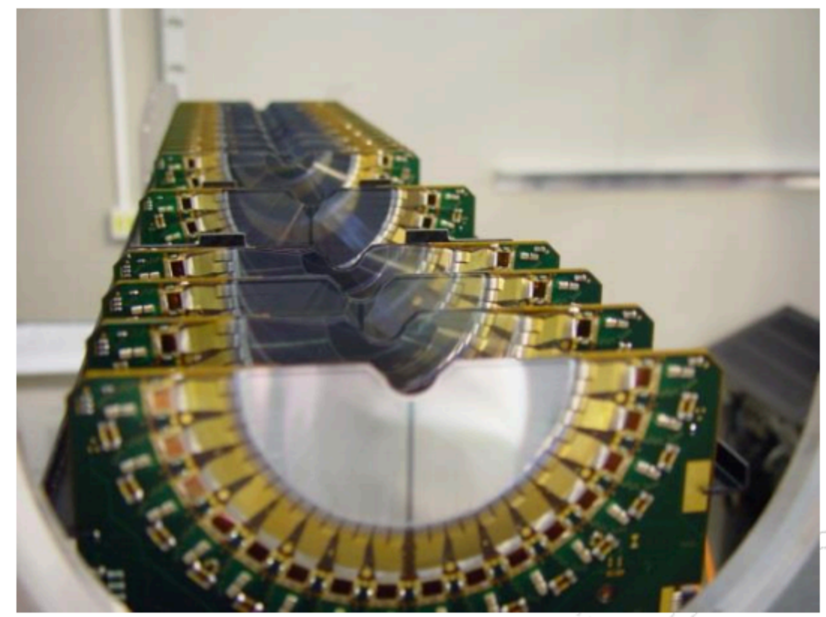


Old VELO detector

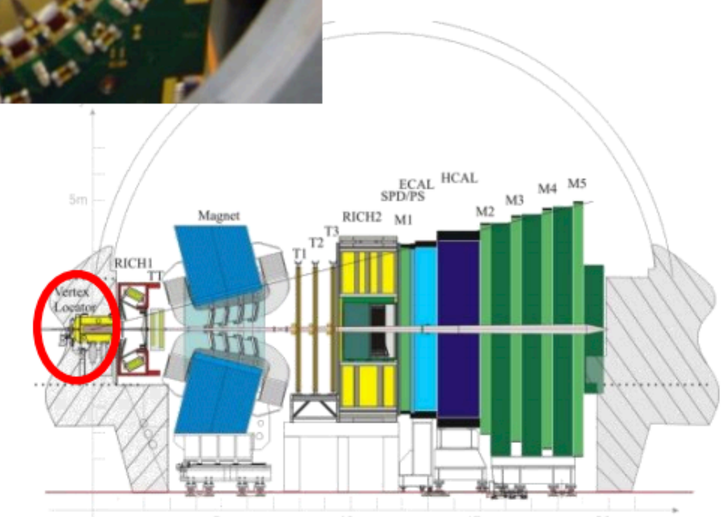
VELO is at the heart of LHCb tracking, trigger and vertexing

- Excellent performance, reliable, cluster efficiency >99%, best hit resolution down to <4μm
- Movable device: from 50 mm to 5 mm, closer to LHC beams during collisions

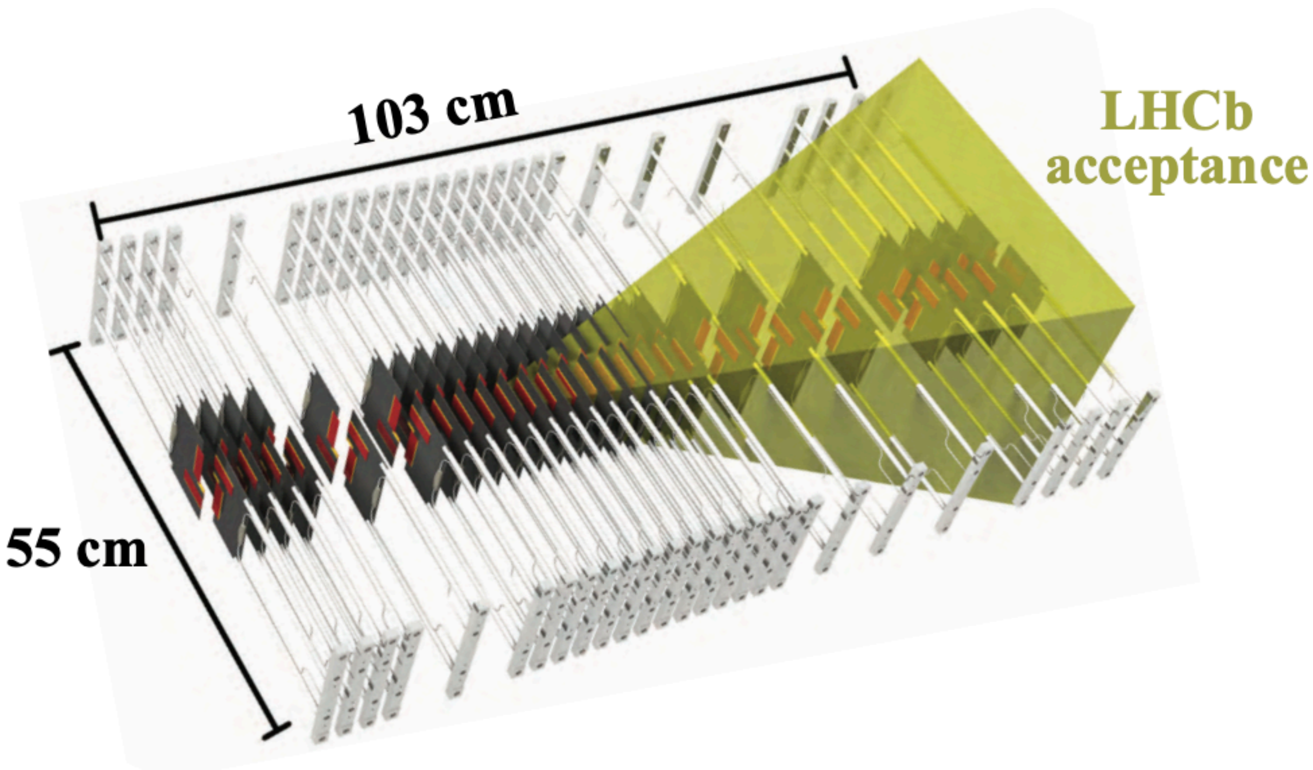


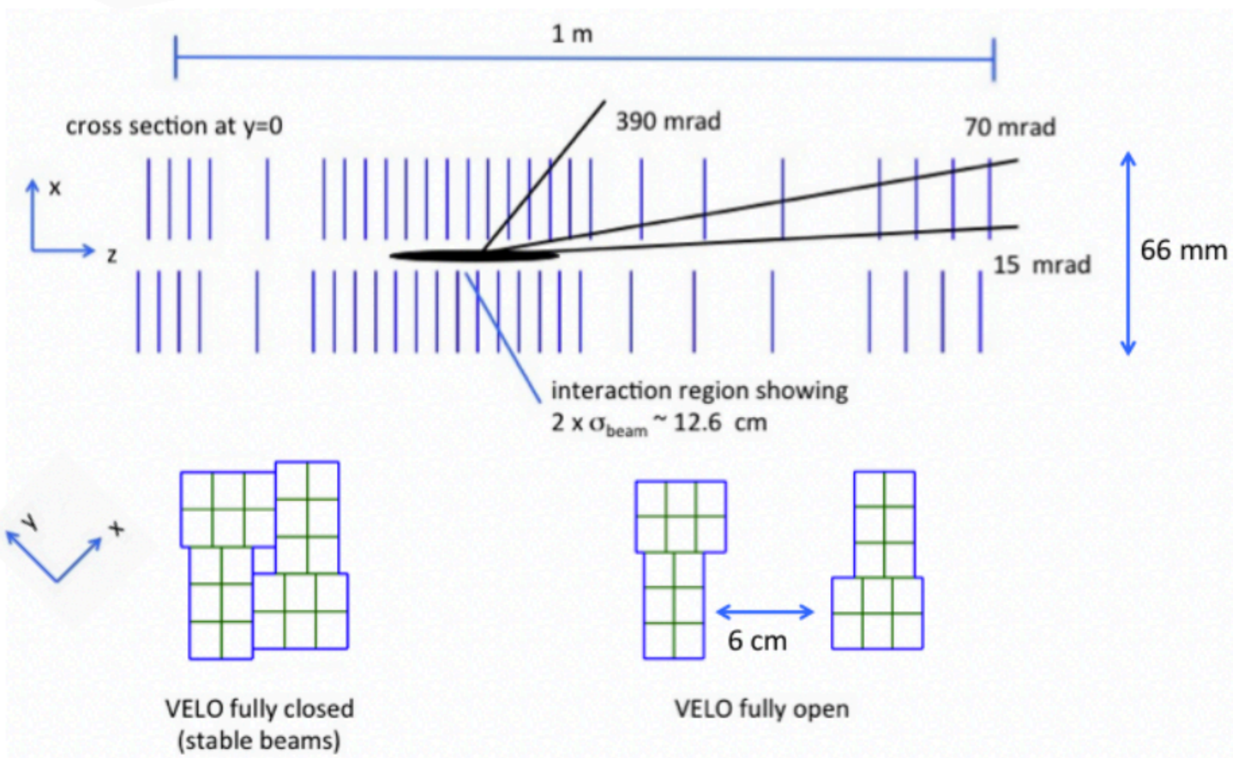


Si-strips measuring r and ϕ



VELO Sensor





	Old VELO	New VELO
Operation years	2010-2018	2022-2030
Sensor	173k R-φ	41M pixels
Num. layers	23	26
Distance from IP	8.2mm	
Fluence	4.3 x 1014	8 x1015
HV tolerance	500 V	1000 V
ASiC readout	1MHz	Data driven
Data Rate	150 Gb/s	2.8 Tb/s
Power	-8 ℃	-25℃

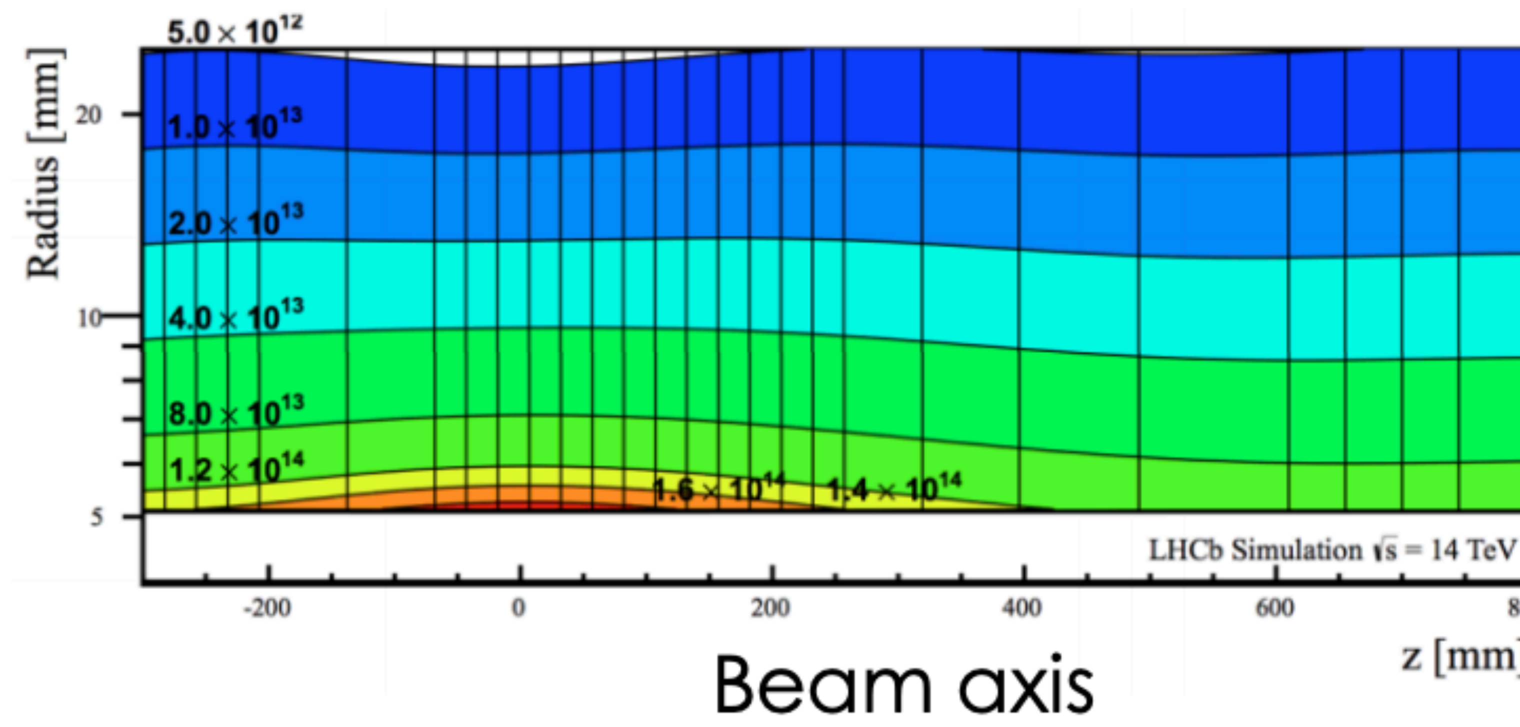
VELO sensor

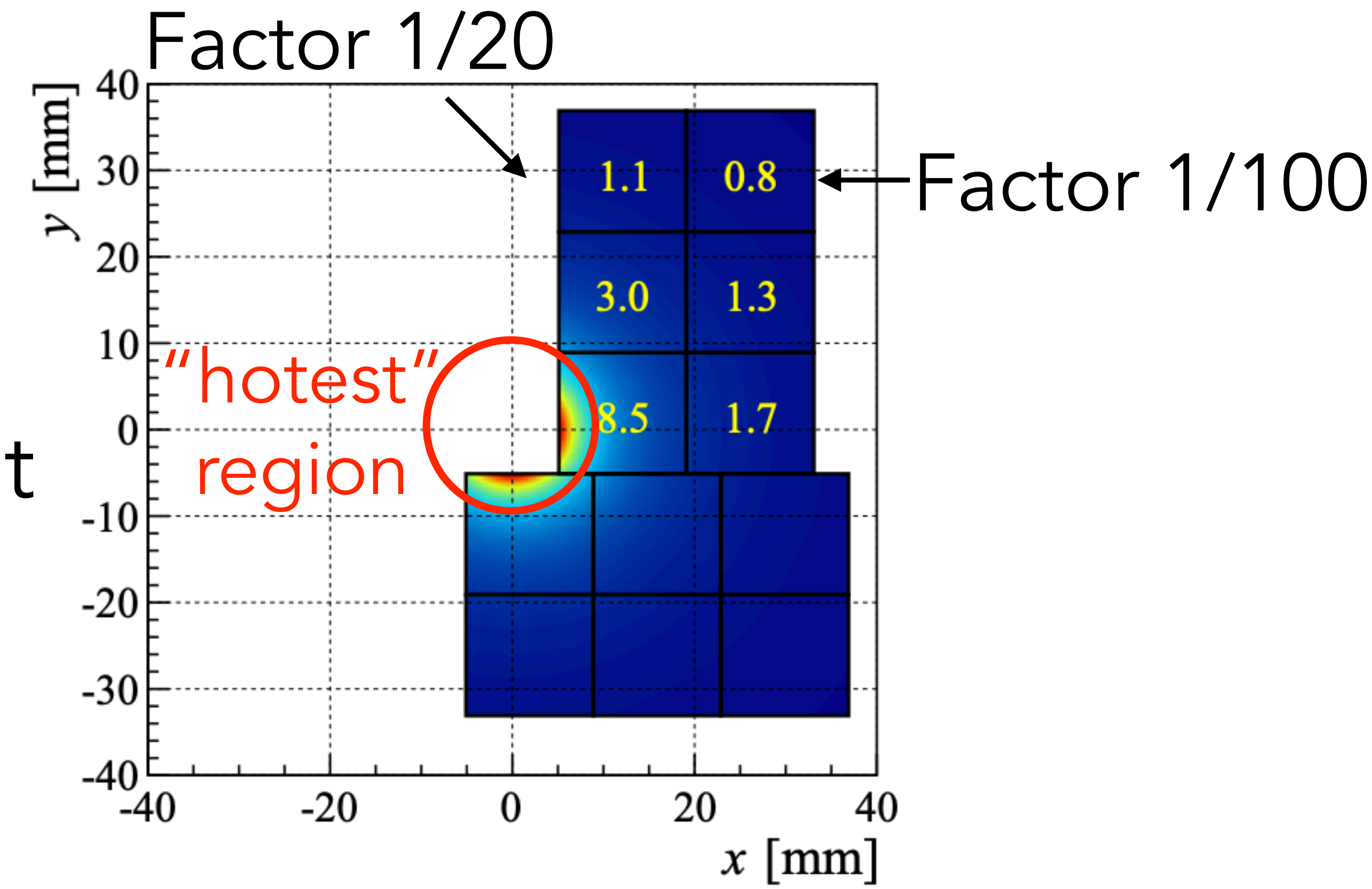
- Collect 6000 e-/MIP
- 99% eff at 370 Mrad

➡Equivalent to 5 years of LHCb Upgrade 50 fb^{-1}

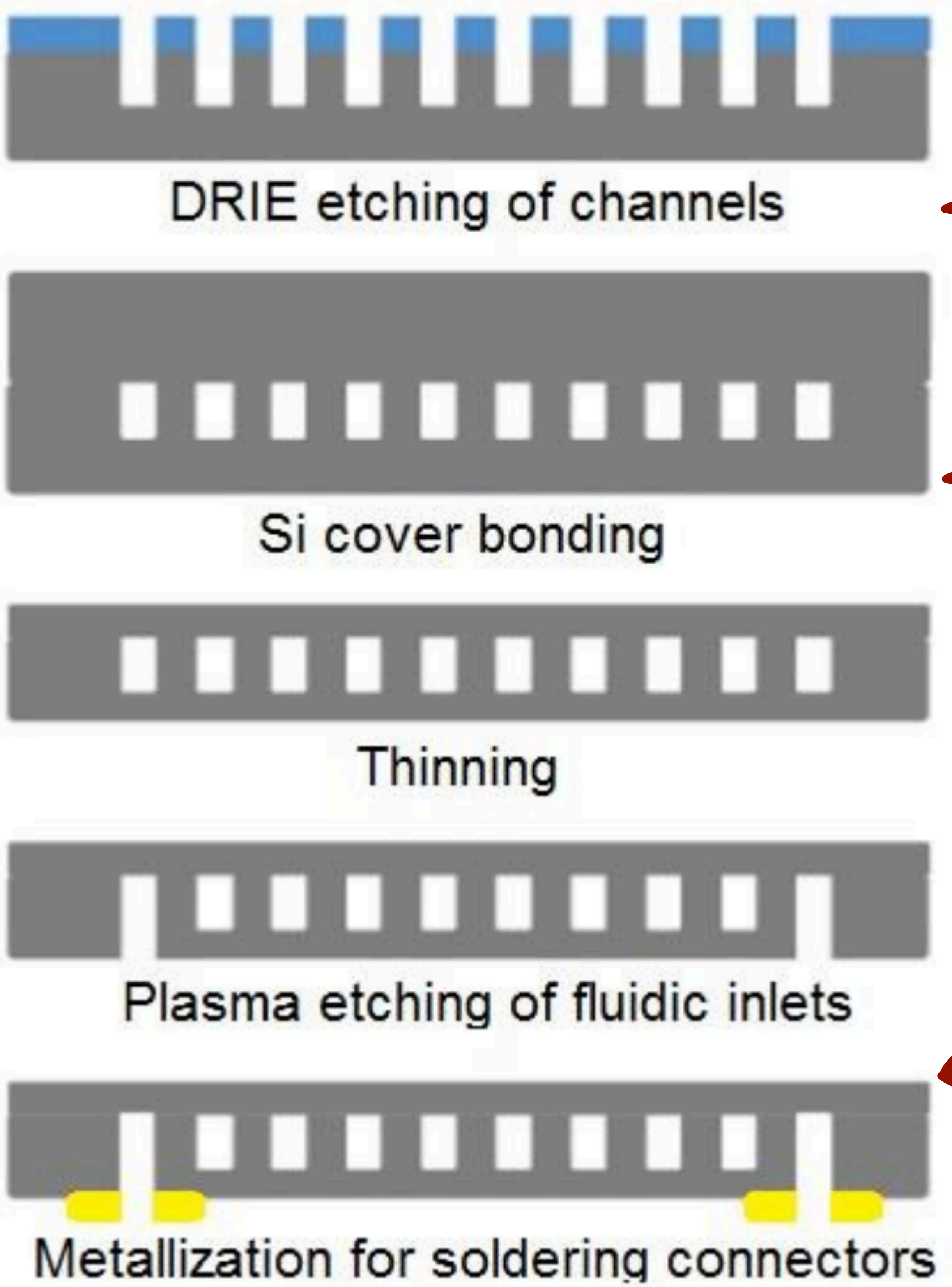
NB: the ATLAS IBL (@ 550 fb^{-1}) expects 3.3 $x10^{15}$ 1 MeV n_{eq}/cm^2 or 160 MRad.

- Mean number of particles crossing an ASIC per event

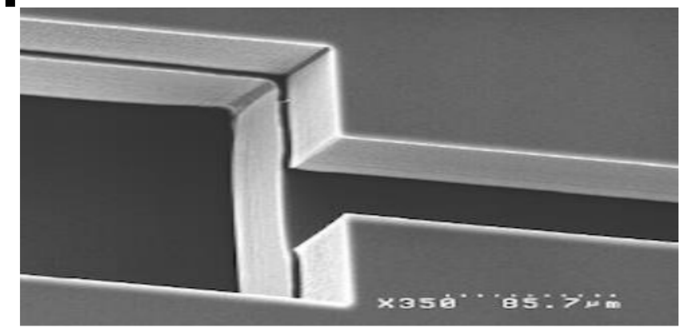




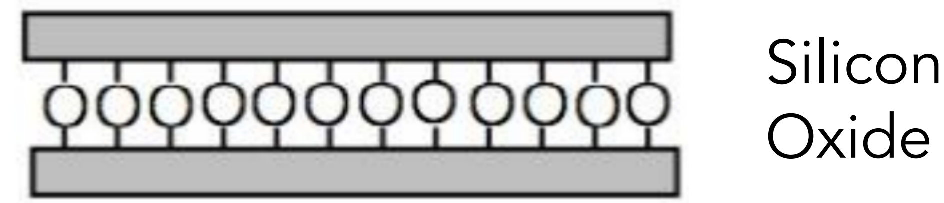
Micro-channel manufacture



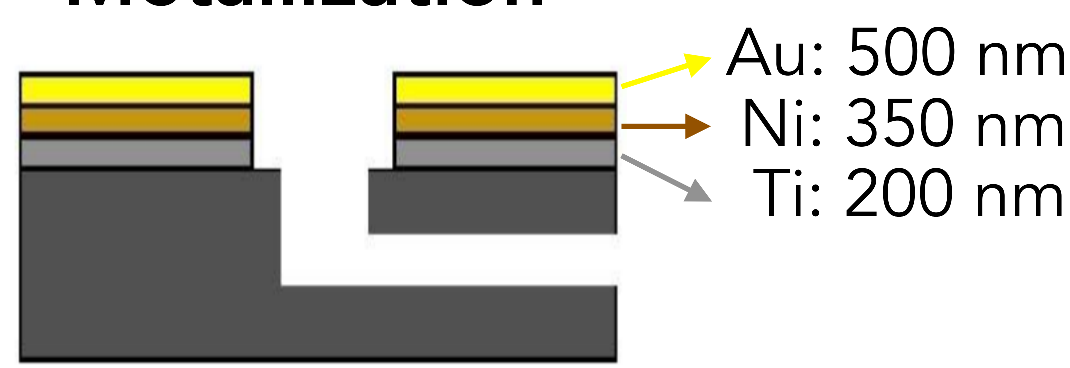
Deep Reactive Ion Etching

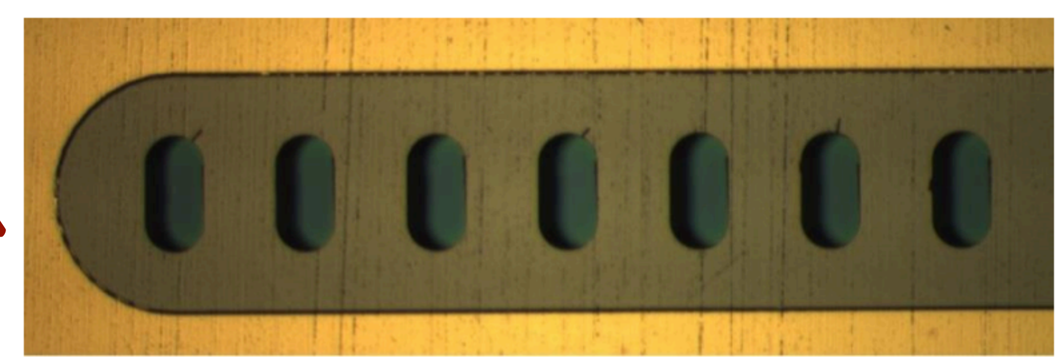


Hydrophilic bonding

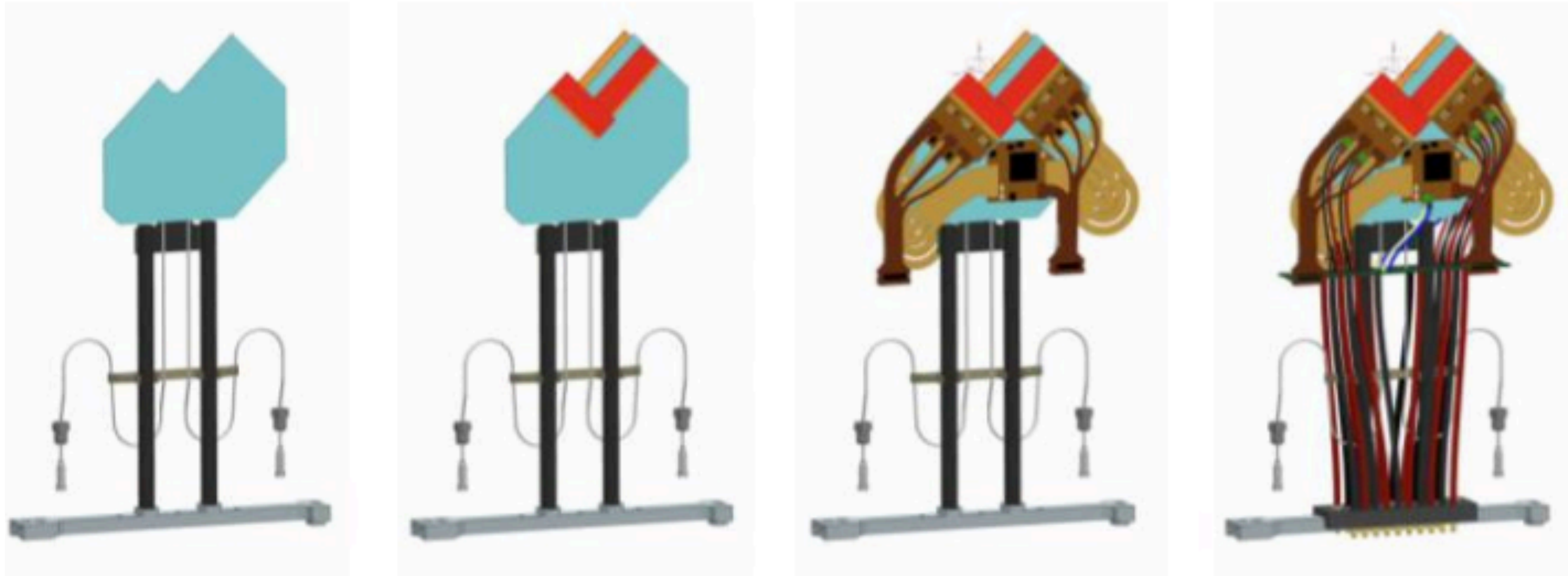


Metallization





Module production

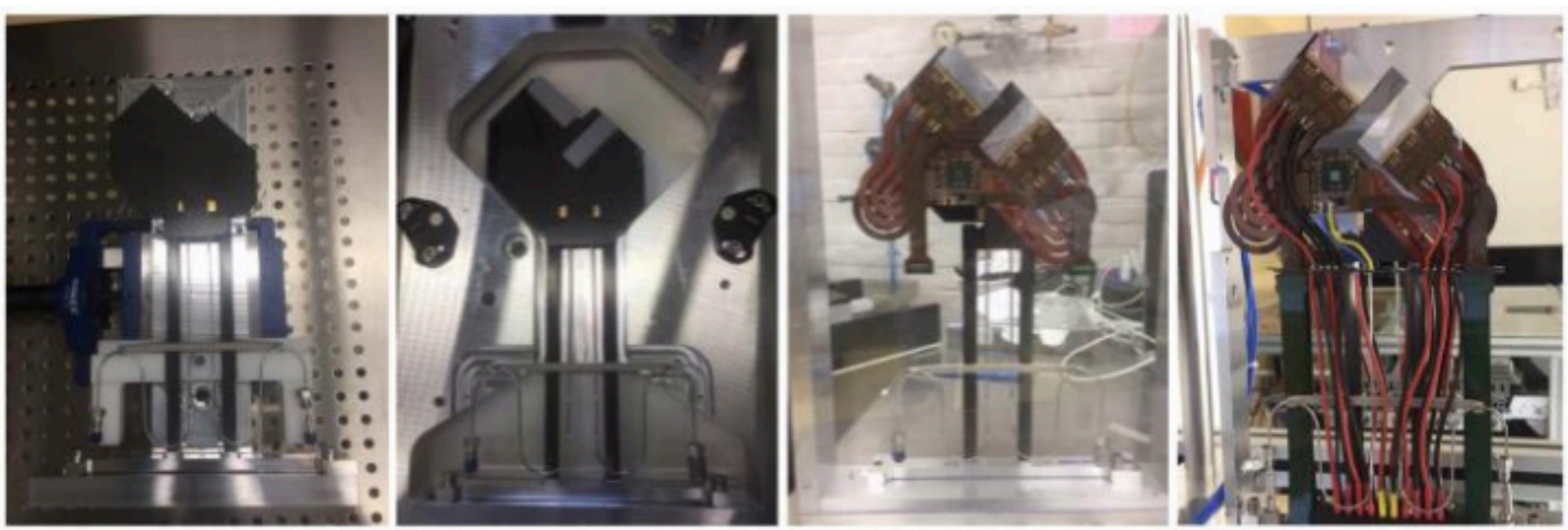


Mechanical construction

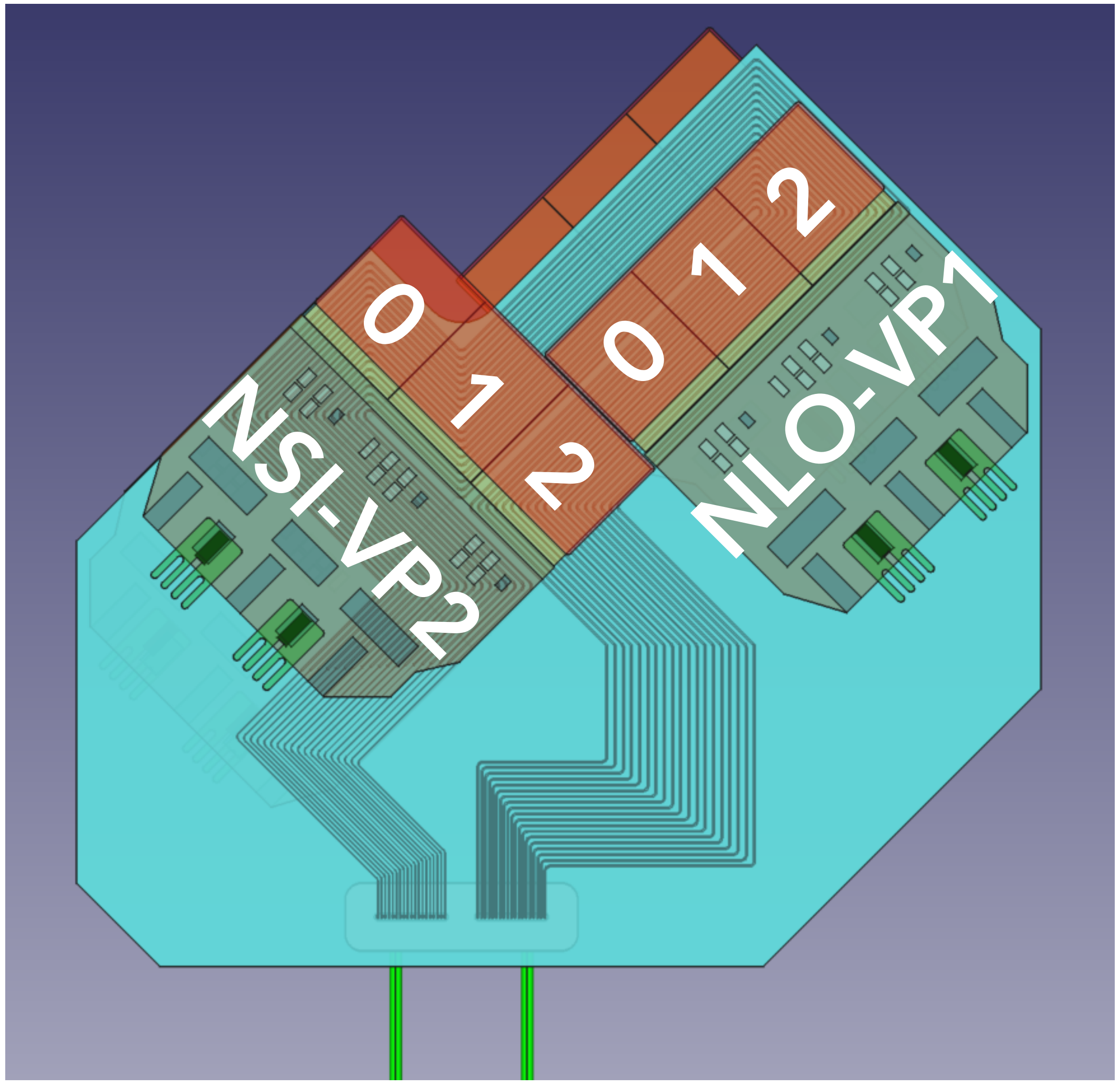
Precision tile placement to 10 µm

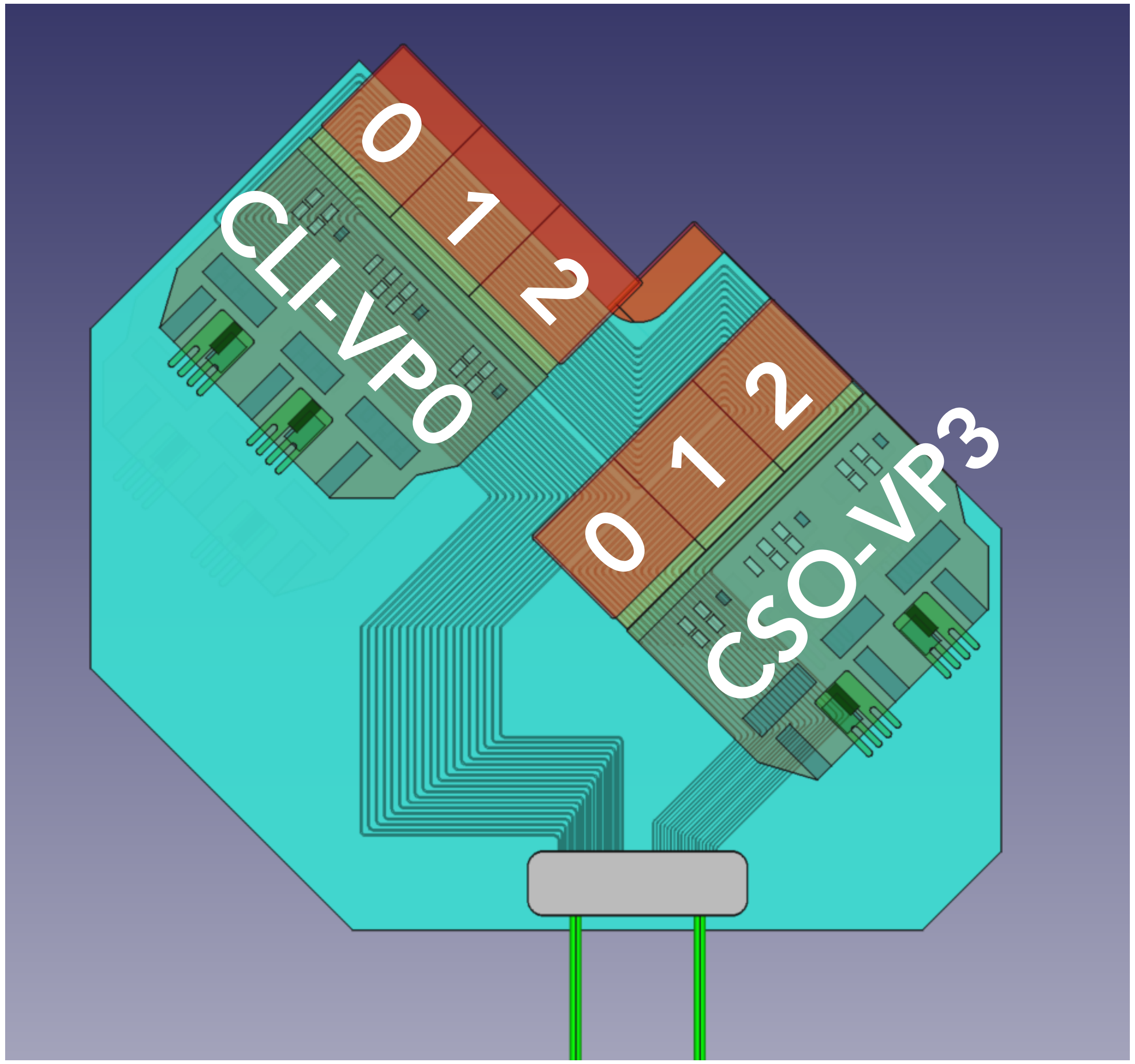
Flex circuit placement

wire bonding and HV/LV/data cable attachment



Module schematic

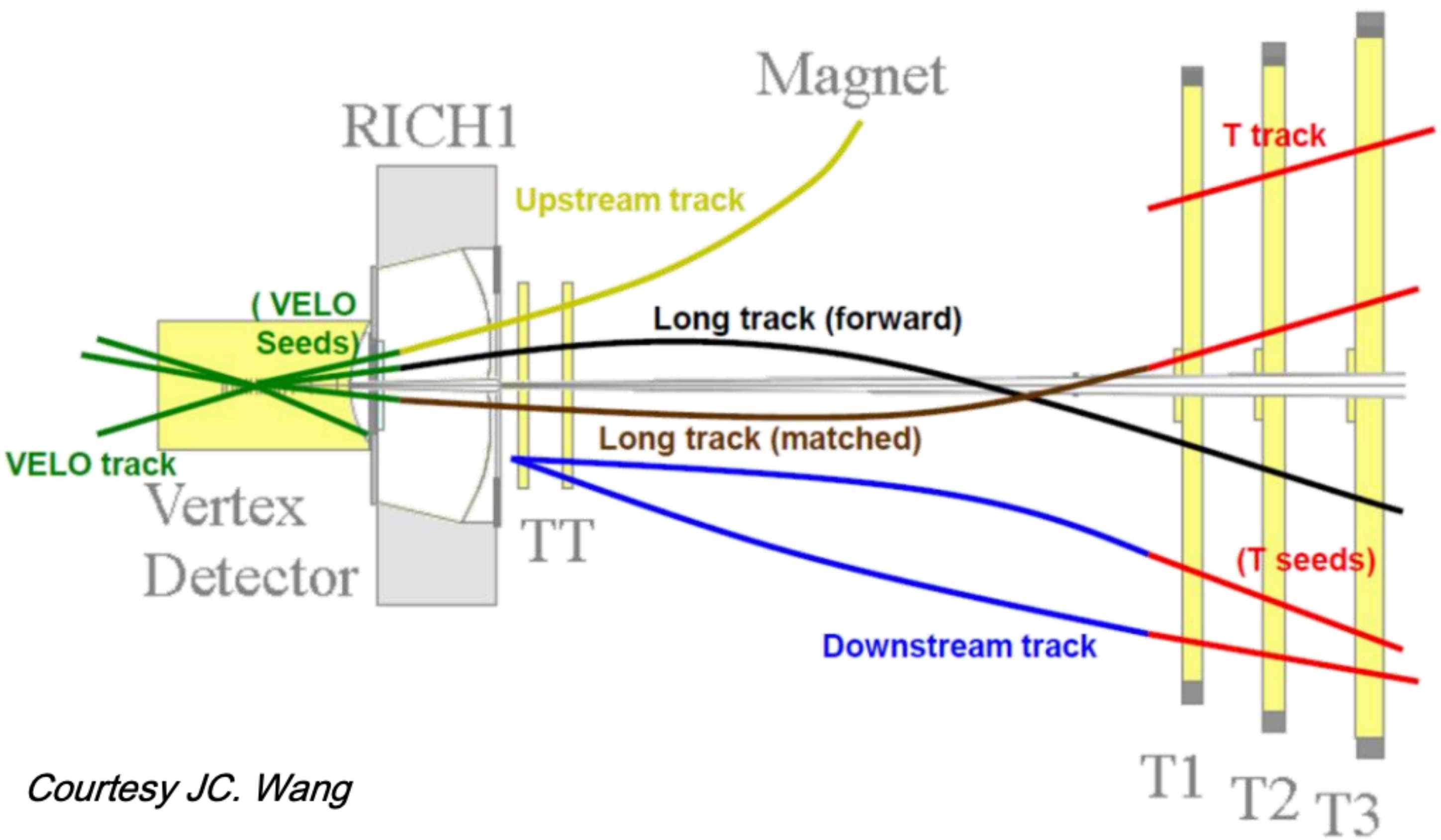




Old Tracking detector

Present Tracking System under upgrade

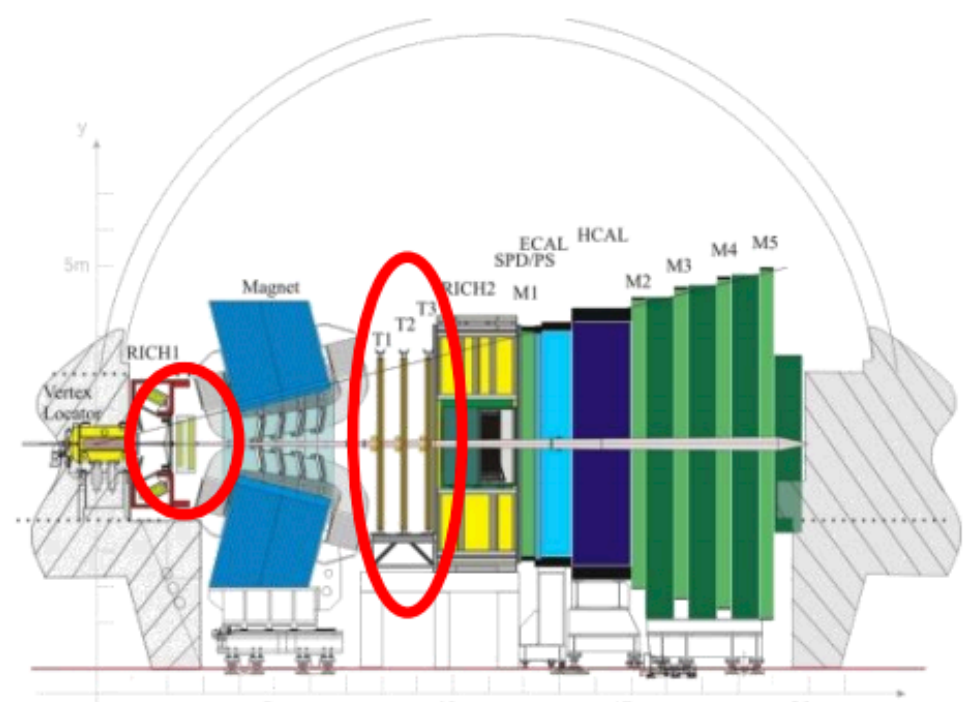
- VELO+**TT**(Si-strip)+Dipole(no change)+**IT**(2% inner area, Si)/**OT**(Straw Tubes)



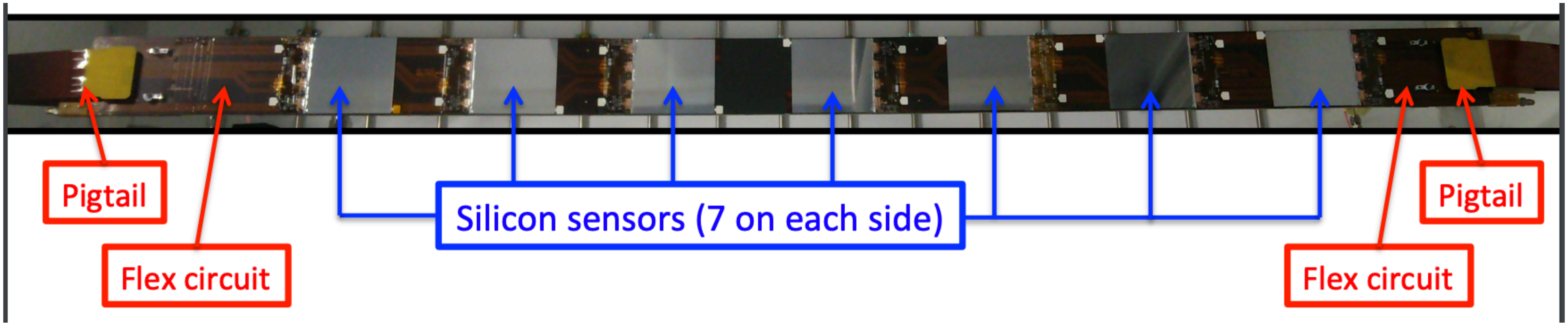
Courtesy JC. Wang

Pattern-recognition based on current tracking system would not be efficient in upgraded scenario

- Too high occupancy in the central region

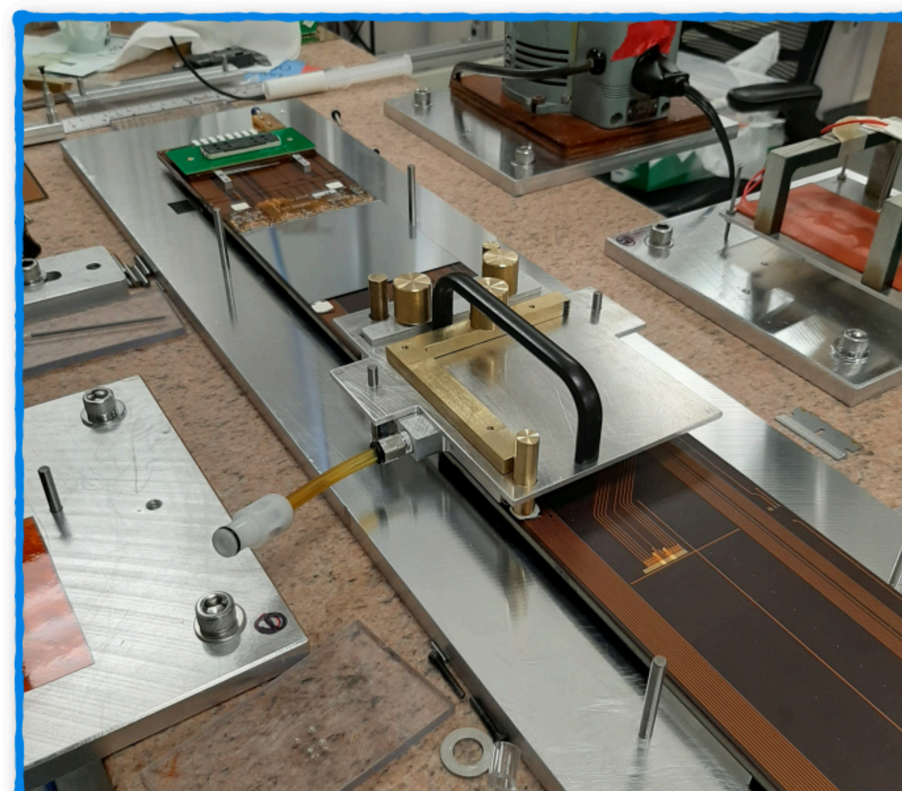


UT: stave in details

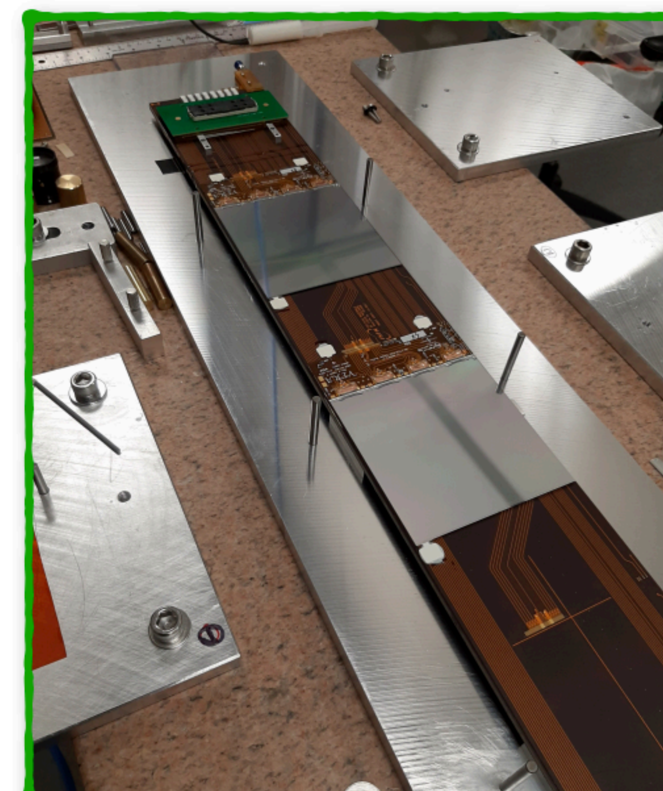


Stencil application of TIM, epoxy, silicone pedestal

Heat TIM, place module, overnight curing



Another module on the stave!

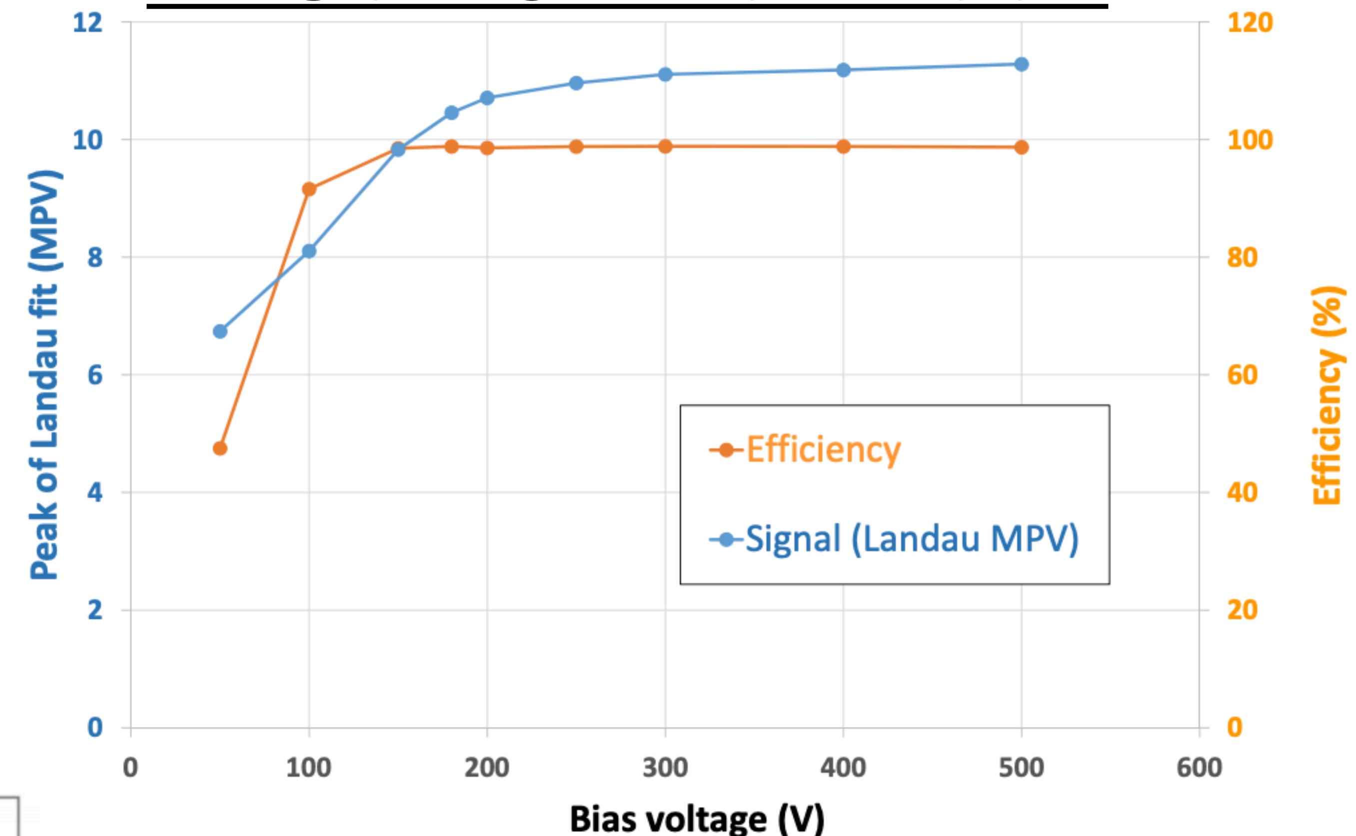


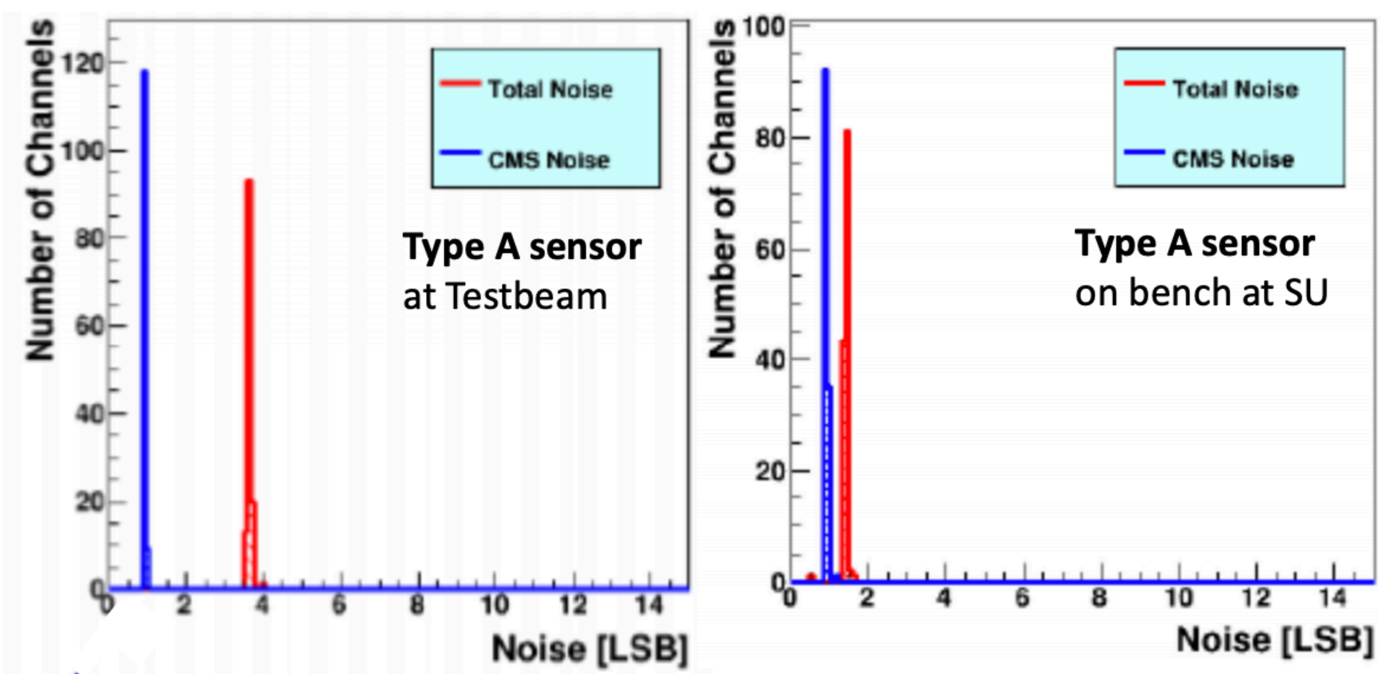
UT: Sensor+ASIC characterisation

LHCb-PUB-2019-009

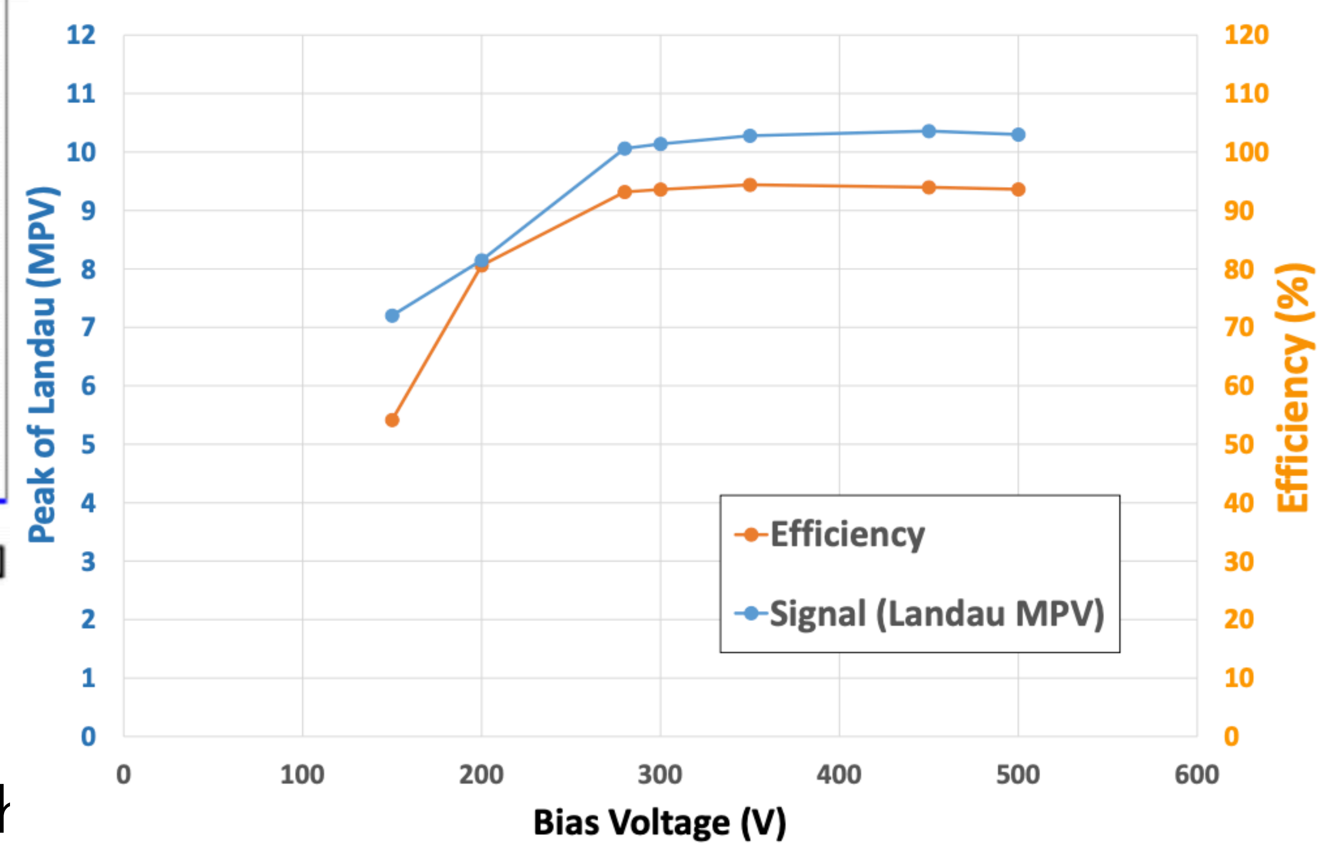
Test beam @ Fermilab

- Type A unirradiated sensor
- 99.5% efficiency and SN~12
- Type B sensor irradiated to 2 x maximal dose
- 94% efficiency and SN~11
  - Readout limitation





Total noise and common-mode subtracted noise for the Type A sensor while in the FTBF testbeam and after the testbeam on the bench

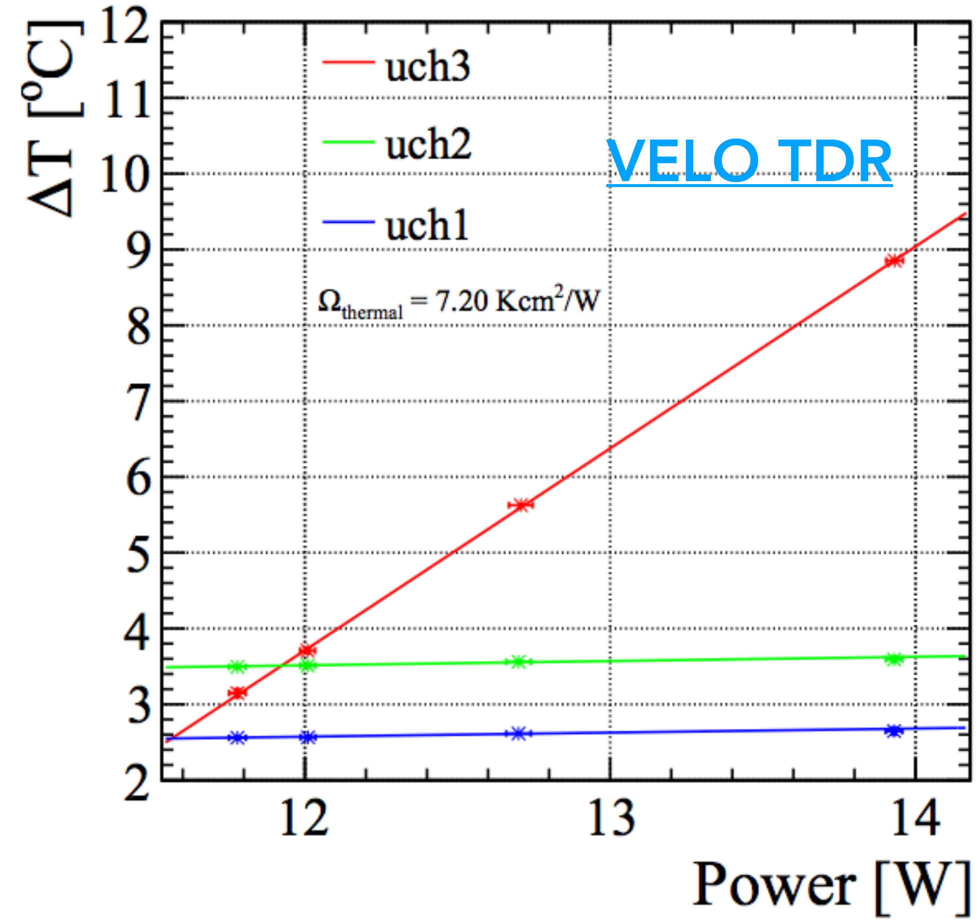


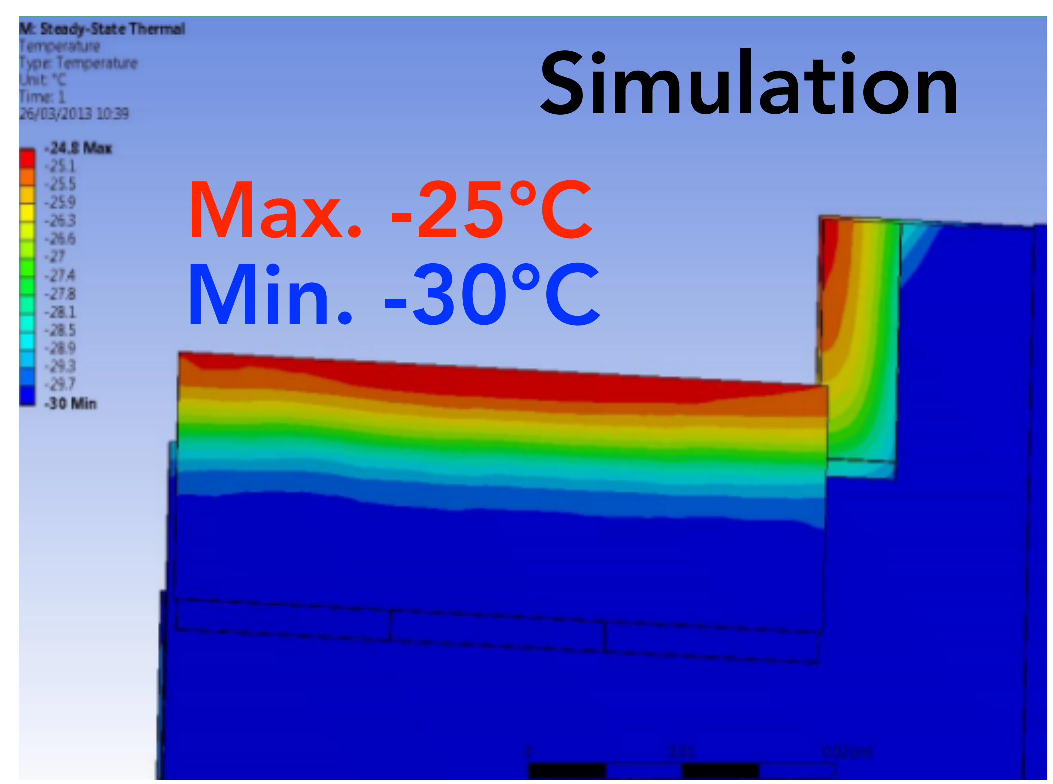
Cooling performance

Cooling performance has been evaluated using thermal mockups emulating half pixel module

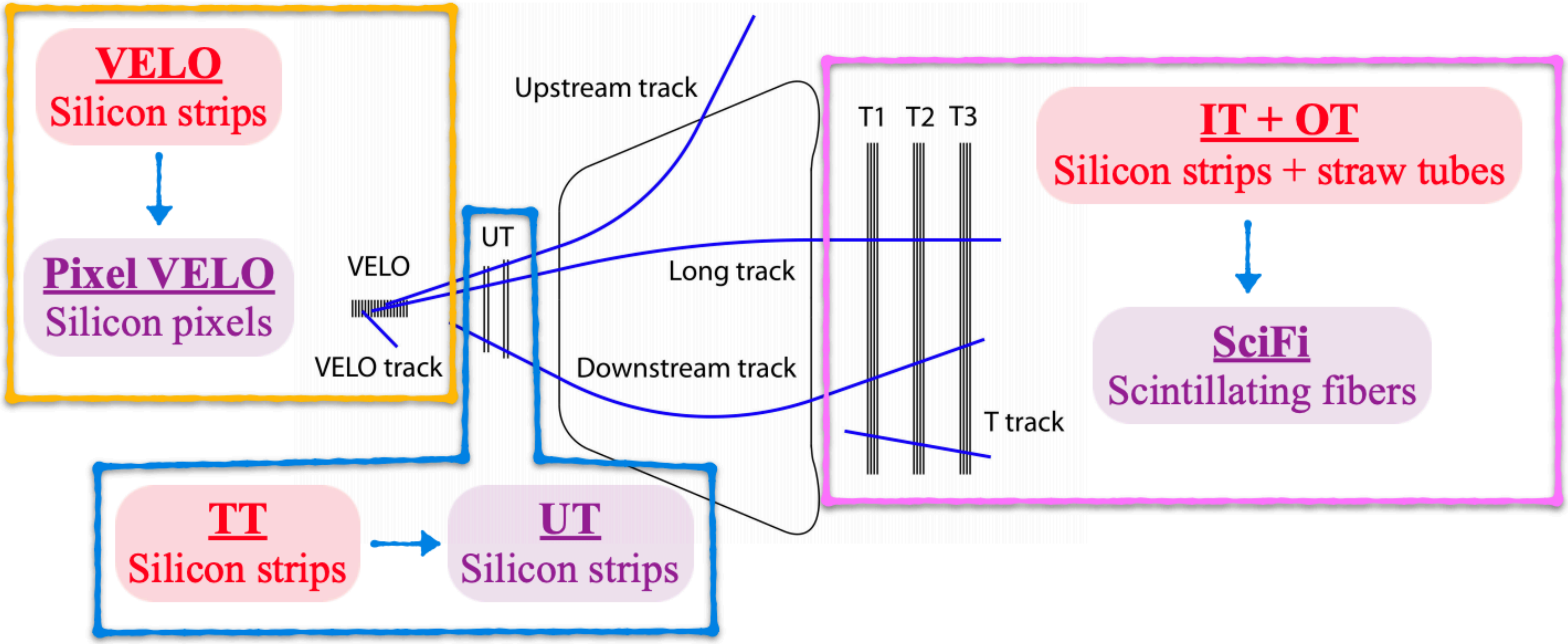
- In nominal conditions, expected 12 W, but tolerates up to 18 W
- The end of-lifetime expectation is 13 W
  - **ΔT(13W) around 6°C**
- Test performed with ASIC heaters at 20 W gives a ΔT~ 6℃
  - Effectiveness of the substrate at providing local cooling
  - ASIC power is concentrated at the part more remote from the silicon tip
- CO_2 normal operation at -30°C corresponds total pressure of 14.28 bar
  - At room temperature the pressure rises to 57.29 bar
  - Operational temperature range is between -40°C and +40°C

Placed at the tip of the mock-sensor





Tracking Upgrade



New tracking able to cope with 50 fb^{-1} plus 40MHz readout, and **improve performance**

- Better **3D impact parameter resolution**: 10-15% improvement in B decay time resolution
- Better **p_T resolution**
- **Gost rate** reduction
- Significant speed up in the reconstruction