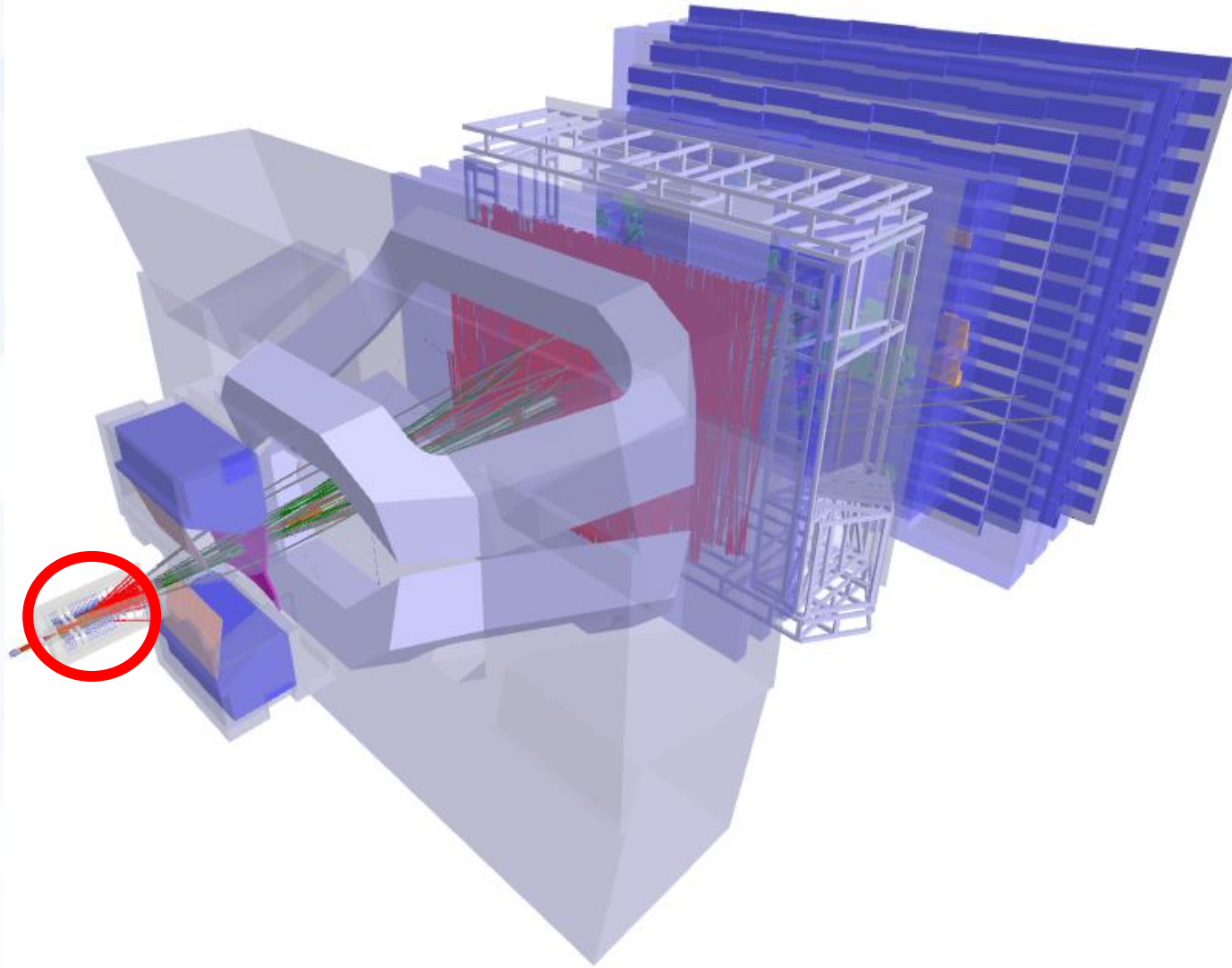


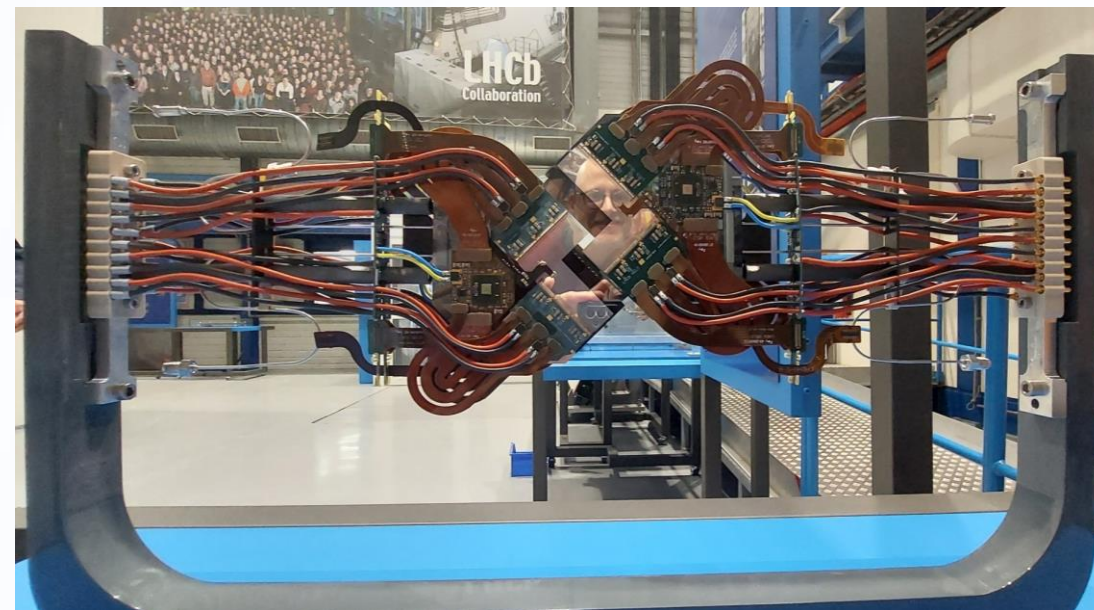
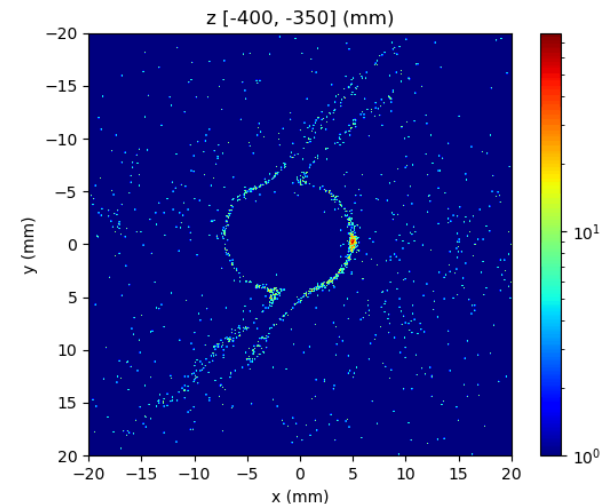
Status of the LHCb Pixel Detector



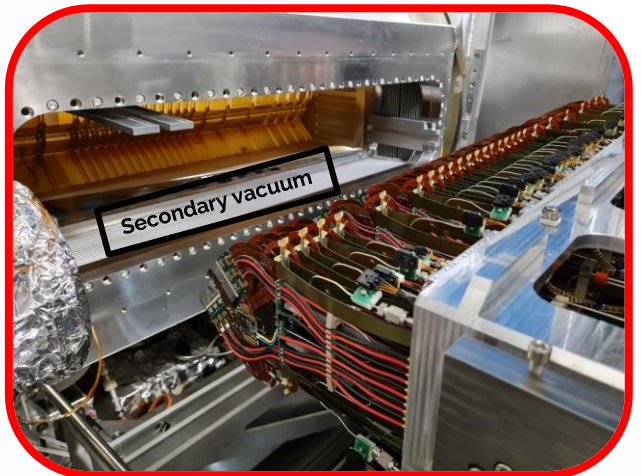
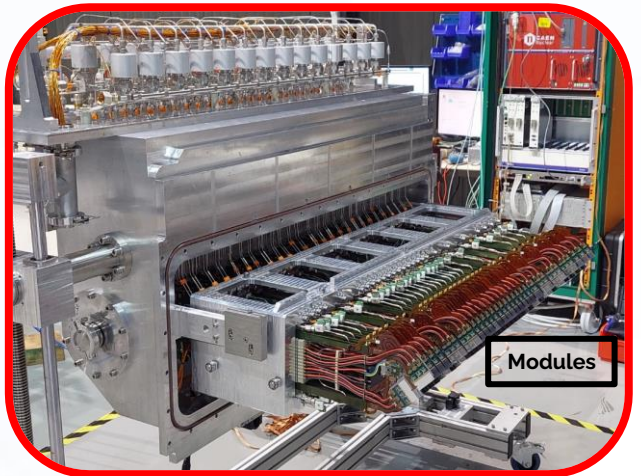
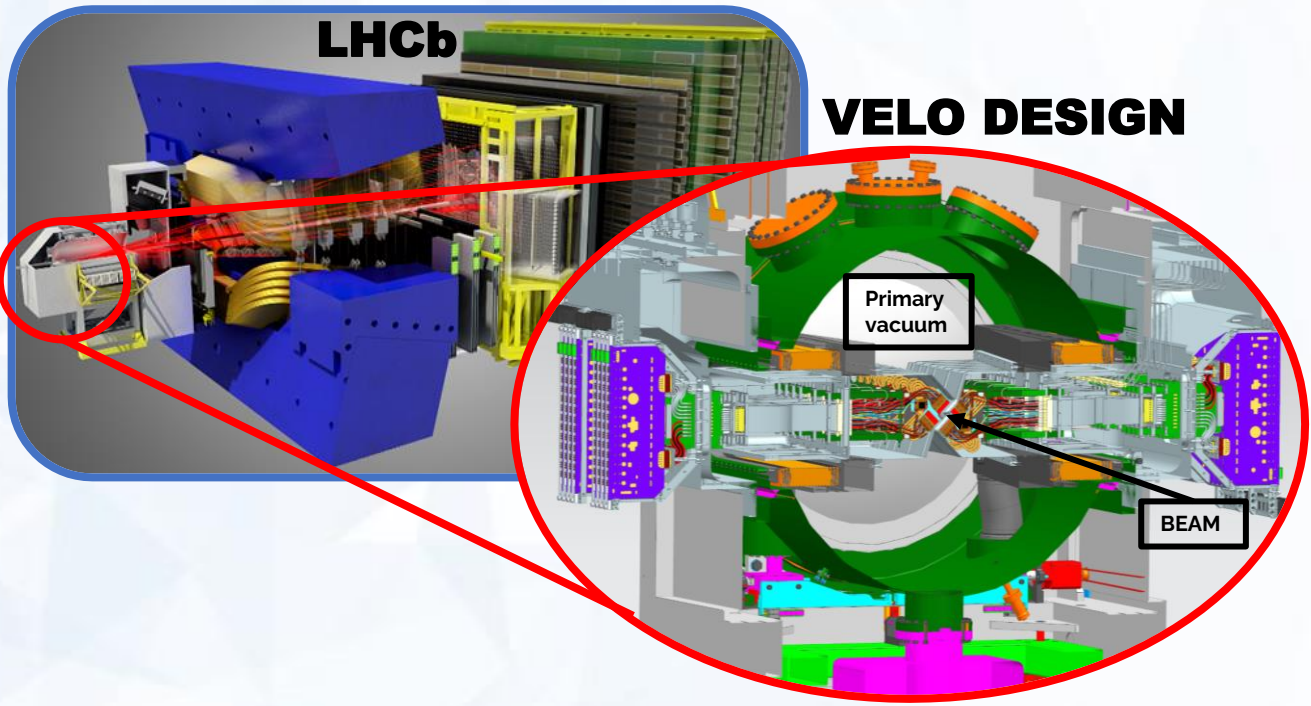
Edgar Lemos Cid, On behalf of the LHCb VELO Group

Outline

- LHCb VELO Upgrade.
- Module Assembly.
- Detector Assembly and Installation.
- VELO Safety System (VSS) and Detector Monitoring.
- VeloPix Calibration: Equalization and Bxid Spread.
- Time Alignment.
- VELO Closing.
- Vertex reconstruction.
- DAQ and FPGA clustering.
- HV performance.
- SMOG 2.



LHCb VELO Upgrade



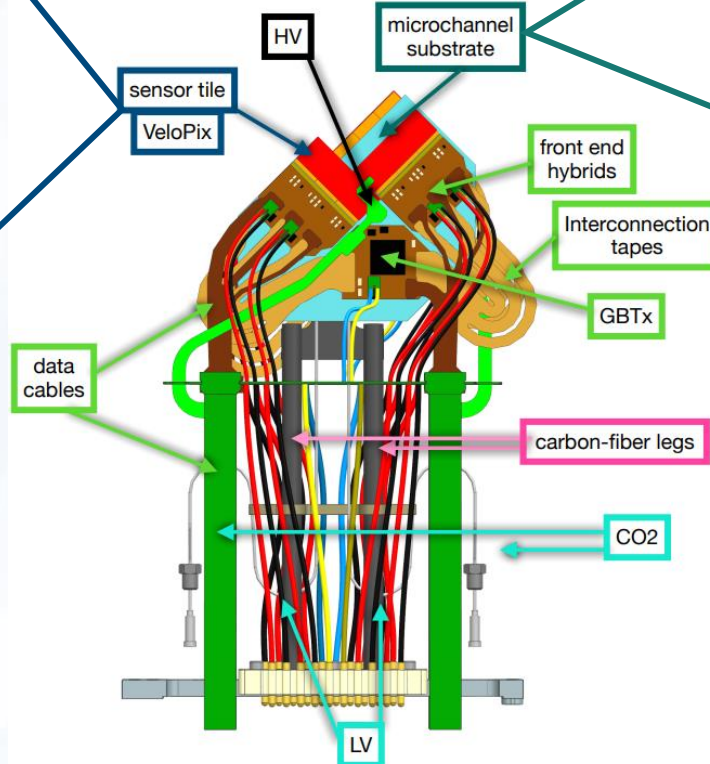
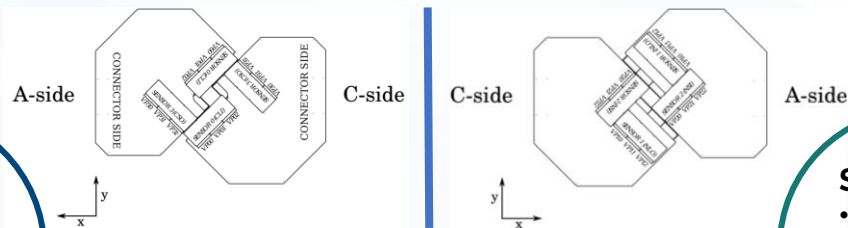
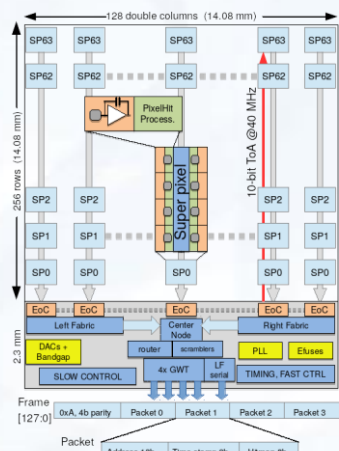
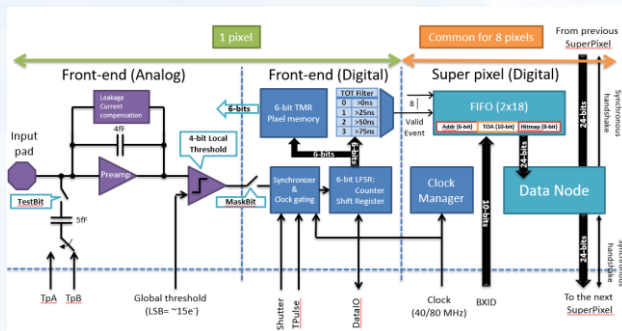
- LHCb is a forward ($2 < \eta < 5$) arm spectrometer focusing in b-hadron and c-hadron decays. Studies CP violation, rare decay, ...
- The Vertex detector (VELO) was successfully updated from silicon strips to pixels in 2022.
 - Closest pixel at 5.1 mm to the LHC beam.
 - Use increased luminosity (5x).
 - Readout all the events at every bunch crossing (40 MHz).

- 41M pixels across 52 modules in vacuum.
- Evaporative CO₂ cooling through microchannels.
- RF foil down to thickness of 150 μ m.

Module Assembly

VeloPix:

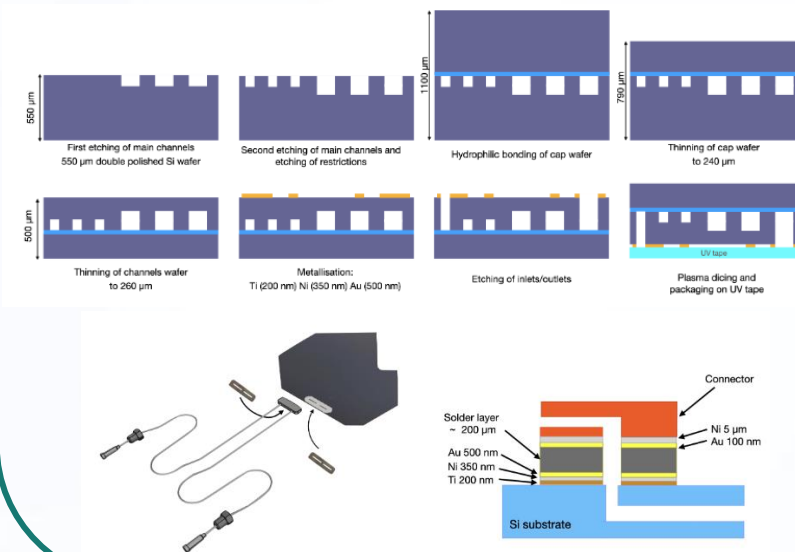
- 256x256 pixels of 55 x 55 μm .
 - 800 Mhits/s/ASIC.
 - Continuous, trigger-less and binary readout.
 - Radiation hard up to 400 Mrad and SEE tolerant.
- *Talk 2018: [VeloPix Readout and ASIC](#).



Silicon microchannel substrates:

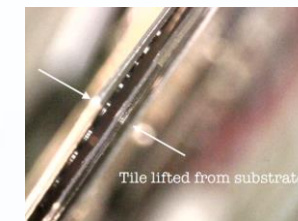
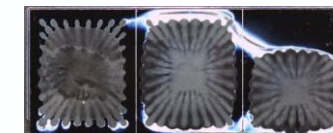
- Two phase evaporative CO₂ cooling.
- 500 μm wafer with 120 x 200 μm^2 microchannels.
- Cooling power up to 40 W at -30 $^{\circ}\text{C}$.

*[Microchannel cooling for the LHCb VELO Upgrade I](#).



Challenges in the way.

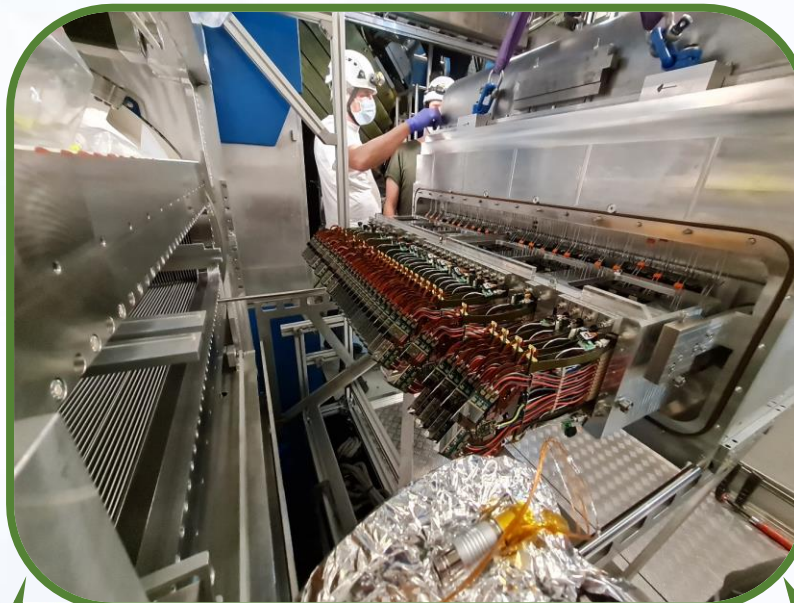
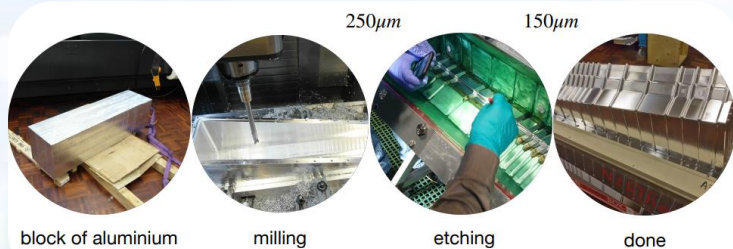
- Glue between ASIC and Substrate.
- GBTx cold operation.
- Connectors metallization.



Detector Assembly and Installation

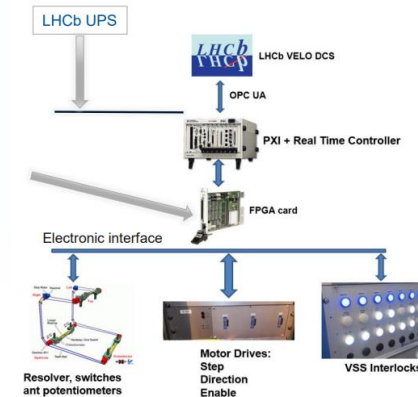
RF Foil:

- 150 μm thick shield that separate VELO vacuum from LHC vacuum.
- 3.5 mm from the beam and 900 μm from the sensors.
- Thermally stable, shield against RF pick-up from the LHC Beam.
- Torlon and Neg coating.



Motion:

- Movement to protect the detector during injection. (Min 3.5 mm).



Cooling:

- 52 microchannel cooling plates boiling at the same time.
- Safety system to avoid CO₂ leaks. Max ΔP of 10 mbar between LHC and VELO vacuum.



Challenges in the way:

- Cooling gasket replacement.
- Feedthrough board replacement.



Metrology:

- μm precision measurement needed.
- Measurements performed at the module assembly, detector assembly (cold) and before detector installation (Foil & Modules).



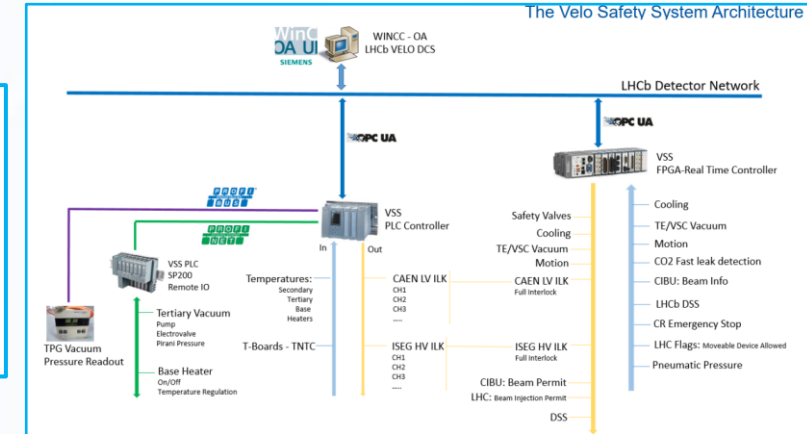
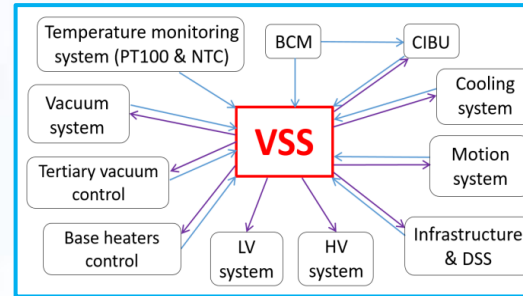
VELO Safety System (VSS) and Detector Monitoring

Detector Monitoring:

- Monitoring of 1209 temperatures, LV and HV. 624 more to add one per VeloPix bandgap.
- Readings from Vacuum system, SMOG 2 system, cooling plant.

VELO Safety System:

Subsystems interrelation



VSS VELO INPUTS C-SIDE											
PT100					NTC						
Signal	Temp	HW	SW	Temp Low	Temp HI	Signal	Temp	HW	SW	Temp Low	Temp HI
INLET1	016.30	●	●	●	●	MODULE_42_OUTLET	-028.20	●	●	●	●
INLET2	-019.10	●	●	●	●	MODULE_44_OUTLET	-028.70	●	●	●	●
MODULE_00_OUTLET	-025.40	●	●	●	●	MODULE_46_OUTLET	-028.00	●	●	●	●
MODULE_02_OUTLET	-029.20	●	●	●	●	MODULE_48_OUTLET	-029.00	●	●	●	●
MODULE_04_OUTLET	-027.70	●	●	●	●	MODULE_50_OUTLET	-028.30	●	●	●	●
MODULE_06_OUTLET	-028.60	●	●	●	●	EXP_VOL_MODULE_06-02	+019.50	●	●	●	●
MODULE_08_OUTLET	-028.90	●	●	●	●	EXP_VOL_MODULE_06-06	+019.50	●	●	●	●
MODULE_10_OUTLET	-028.80	●	●	●	●	EXP_VOL_MODULE_08-10	+019.40	●	●	●	●
MODULE_12_OUTLET	-028.80	●	●	●	●	EXP_VOL_MODULE_12-14	+019.20	●	●	●	●
MODULE_14_OUTLET	-029.20	●	●	●	●	EXP_VOL_MODULE_16-18	+019.20	●	●	●	●
MODULE_16_OUTLET	-029.20	●	●	●	●	EXP_VOL_MODULE_20-22	+018.50	●	●	●	●
MODULE_18_OUTLET	-028.90	●	●	●	●	EXP_VOL_MODULE_24-26	+018.70	●	●	●	●
MODULE_20_OUTLET	-029.10	●	●	●	●	EXP_VOL_MODULE_28-30	+018.60	●	●	●	●
MODULE_22_OUTLET	-028.40	●	●	●	●	EXP_VOL_MODULE_30-34	+018.90	●	●	●	●
MODULE_24_OUTLET	-028.40	●	●	●	●	EXP_VOL_MODULE_36-38	+018.80	●	●	●	●
MODULE_26_OUTLET	-027.60	●	●	●	●	EXP_VOL_MODULE_40-42	+018.90	●	●	●	●
MODULE_28_OUTLET	-028.30	●	●	●	●	EXP_VOL_MODULE_44-46	+019.00	●	●	●	●
MODULE_30_OUTLET	-028.30	●	●	●	●	EXP_VOL_MODULE_48-50	+019.00	●	●	●	●
MODULE_32_OUTLET	-027.70	●	●	●	●	OUTLET_1	-029.90	●	●	●	●
MODULE_34_OUTLET	-028.40	●	●	●	●	OUTLET_2	+029.70	●	●	●	●
MODULE_36_OUTLET	-028.70	●	●	●	●	AIR_FIRST	+006.50	●	●	●	●
MODULE_38_OUTLET	-028.10	●	●	●	●	AIR_LAST	+001.50	●	●	●	●
MODULE_40_OUTLET	-029.10	●	●	●	●	EXP_VOLUME_CAP	-000.70	●	●	●	●
VALVE_BELL	-020.20	●	●	●	●	BYPASS_VALVE	-017.80	●	●	●	●

VSS VELO OUTPUTS C-SIDE									
HV Interlocks					LV Interlocks				
Signal	HW	SW	Limit	Signal	HW	SW	Limit	Signal	HW
Foil 1	●	●	Low	LV_HV_MOD_00-02-04	●	●	●	LV_HV_MOD_00-02-04	●
Foil 2	●	●	High	LV_HV_MOD_06-08-10	●	●	●	LV_HV_MOD_06-08-10	●
Foil 3	●	●	High	LV_HV_MOD_12-14-16	●	●	●	LV_HV_MOD_12-14-16	●
Foil 4	●	●	High	LV_HV_MOD_18-20-22	●	●	●	LV_HV_MOD_18-20-22	●
				LV_HV_MOD_24-26-28	●	●	●	LV_HV_MOD_24-26-28	●
				LV_HV_MOD_30-32-34	●	●	●	LV_HV_MOD_30-32-34	●
				LV_HV_MOD_36-38-40	●	●	●	LV_HV_MOD_36-38-40	●
				LV_HV_MOD_42-44-46	●	●	●	LV_HV_MOD_42-44-46	●
				LV_HV_MOD_48-50	●	●	●	LV_HV_MOD_48-50	●
				LV_OPB_MOD_06to16	●	●	●	LV_OPB_MOD_06to16	●
				LV_OPB_MOD_18to34	●	●	●	LV_OPB_MOD_18to34	●
				LV_OPB_MOD_36to50	●	●	●	LV_OPB_MOD_36to50	●

COOLING AND VACUUM									
Signal	HW	SW	Limit	Signal	HW	SW	Limit	Signal	HW
COOLING_A_SIDE_OK	●	●	●	OS2AR	●	●	●	DSI_NO_EMERGENCY	●
COOLING_C_SIDE_OK	●	●	●	OS3BEAR/OL	●	●	●	SNIFFER_IN_RANGE	●
COOLING_POWER_OK	●	●	●	VACUUM_OK	●	●	●	VSS Digital Input	●
COOLING_AT_SETPOINT	●	●	●	TERTIARY_VACUUM_OK	●	●	●	NO_CO2_LEAK	●
COOLING_FULL_AVAILABLE	●	●	●	NO_CO2_LEAK	●	●	●	VACUUM_OK ORINO_CO2_LEAK AND GIS READY	●

VELO Safety System (VSS) and Detector Monitoring

Detector Monitoring:

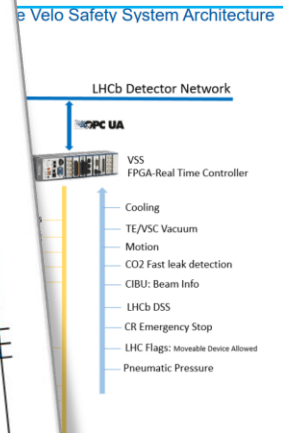
- Monitoring of 1209 temperatures, LV and HV. 624 more to add one per VeloPix bandgap.
- Readings from Vacuum system, SMOG 2 system, cooling plant.

VELO Safety System:

- Temperature system
- Vacuum system
- Tertiary vacuum control
- Base heat control

VSS Matrix

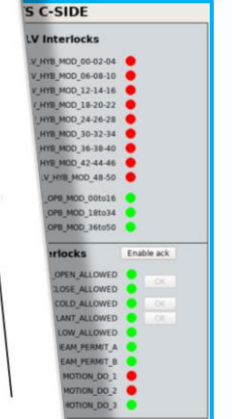
	CO2 SAFETY VALVE C. SIDE OPEN ALLOWED	CO2 BYPASS VALVE C. SIDE CLOSE ALLOWED	HV C. SIDE ALLOWED	LV MOD. C. SIDE ALLOWED	LV OPB C. SIDE ALLOWED	CO2 SAFETY VALVE A. SIDE OPEN ALLOWED	CO2 BYPASS VALVE A. SIDE CLOSE ALLOWED	HV A. SIDE ALLOWED	LV MOD. A. SIDE ALLOWED	LV OPB A. SIDE ALLOWED	VELO IN ALLOWED	VELO MOVEMENT ALLOWED	VELO NOT OUT EMERGENCY	COOLING PLANT ALLOWED	COOLING COLD ALLOWED	BEAM PERMIT A	BEAM PERMIT B	SHUTTER IN RANGE (ALCOVE, SHOWER, DR)	SHUTTER IN RANGE (WATER COOLING, CR)	VACUUM ALLOWED	VENTING ALLOWED	COOLING PLANT FLOW ALLOWED	
knowledge	yes																						
CLUM OK																							
CLUM OK OR GIS READY																							
DRIP OK																							
DRIP/MVOL OK																							
CO2 LEAK																							
STAIRY VACUUM OK																							
3 OK																							
COOLING POWER OK																							
COOLING AT SETPOINT																							
CR OUT NO EMERGENCY																							
CR IN RANGE																							
CR MOVING																							
CR MOVING AND VENTING ALLOWED BUTTON																							
CR WATER IN RANGE																							
CR C SIDE OK																							
CR OK OR A SIDE OPEN																							
CR NET TEMP IN RANGE																							
CR MODULE X OUTLET TEMP IN RANGE																							
CR EXP VOLUME MODULE X-Y TEMP IN RANGE																							
CR OUTLET TEMP IN RANGE																							
CR AIR TEMP IN RANGE																							
CR RFOIL TEMP X NOT LOW																							
CR RFOIL TEMP X NOT HIGH																							
CR HV TEMP MOD X-Y IN RANGE																							
CR SBTX TEMP MOD X-Y IN RANGE																							
CR DBP TEMP MOD X-Y IN RANGE																							
CR DRIVING A SIDE OK																							
CR OK OR A SIDE OPEN																							
CR NET TEMP IN RANGE																							
CR MODULE X OUTLET TEMP IN RANGE																							
CR EXP VOLUME MODULE X-Y TEMP IN RANGE																							
CR OUTLET TEMP IN RANGE																							
CR AIR TEMP IN RANGE																							
CR RFOIL TEMP X NOT LOW																							
CR RFOIL TEMP X NOT HIGH																							
CR HV TEMP MOD X-Y IN RANGE																							
CR SBTX TEMP MOD X-Y IN RANGE																							



PT100

Signal	Tem
INLET1	-016
INLET2	-019.5
MODULE_00_OUTLET	-025.1
MODULE_02_OUTLET	-025.4
MODULE_04_OUTLET	-029.2
MODULE_06_OUTLET	-027.7
MODULE_08_OUTLET	-028.6
MODULE_10_OUTLET	-028.9
MODULE_12_OUTLET	-028.8
MODULE_14_OUTLET	-029.2
MODULE_16_OUTLET	-029.2
MODULE_18_OUTLET	-028.9
MODULE_20_OUTLET	-029.1
MODULE_22_OUTLET	-028.9
MODULE_24_OUTLET	-028.4
MODULE_26_OUTLET	-027.6
MODULE_28_OUTLET	-028.3
MODULE_30_OUTLET	-028.3
MODULE_32_OUTLET	-027.7
MODULE_34_OUTLET	-028.4
MODULE_36_OUTLET	-028.7
MODULE_38_OUTLET	-028.1
MODULE_40_OUTLET	-029.1
VALVE_BELL	-020.2

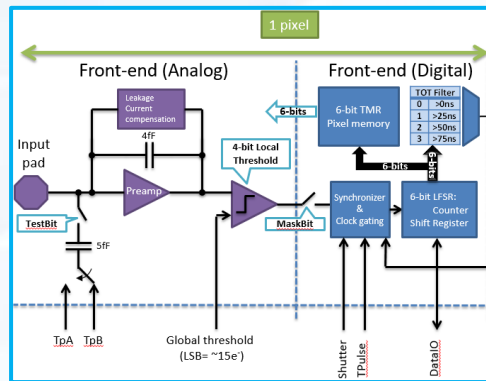
COOLING AND VACUUM



VeloPix Calibration: Equalization & Bxid Spread

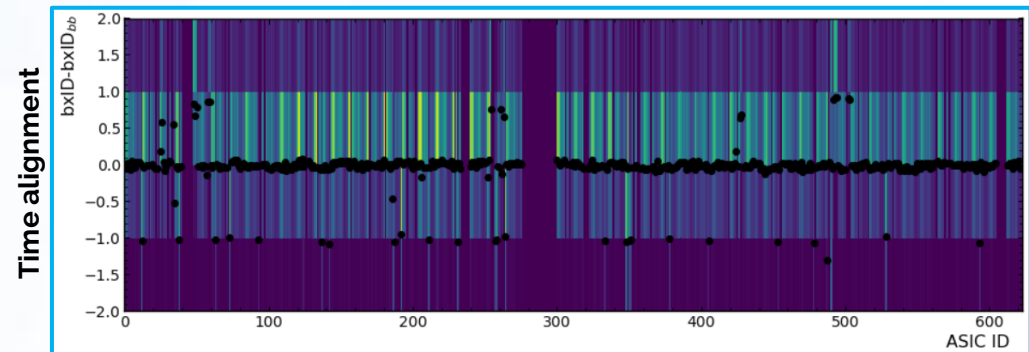
Equalization:

- Estimated using the noise baseline at different threshold values.
- 16 fine tune values per each pixel.
- Use the extreme values (0, 15) for global Threshold scan and calculation of the optimal value.

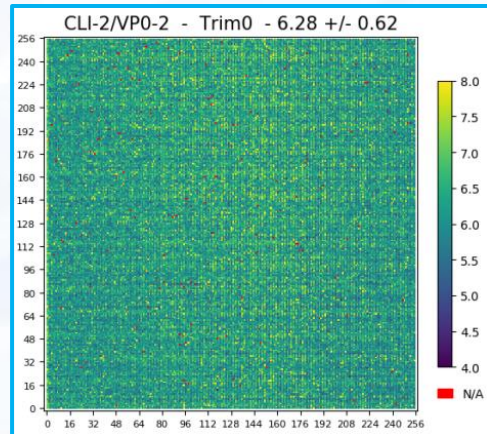


Bxid spread:

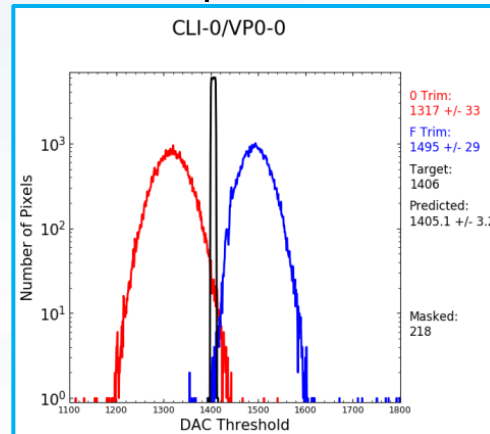
- Equalization not tuned in terms of analog circuit parameters and threshold. First approach to keep the same settings for the full detector.
- During time alignment. ToA Bxid different in pixels of the same ASIC. Analog TP see the same effect.
- DAC scan and Threshold set to eliminate this effect.



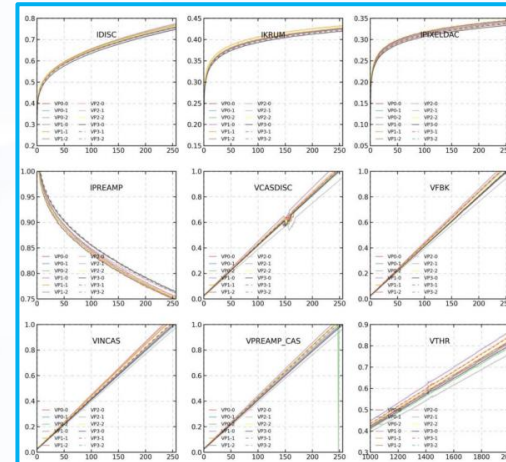
Noise



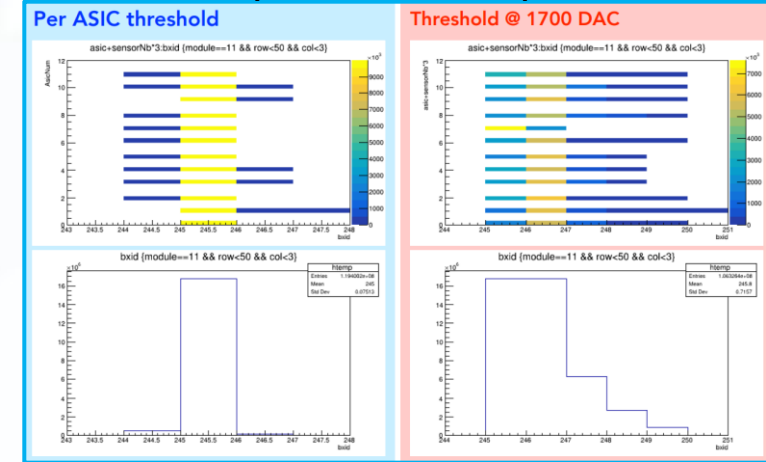
Equalization



DAC Scan

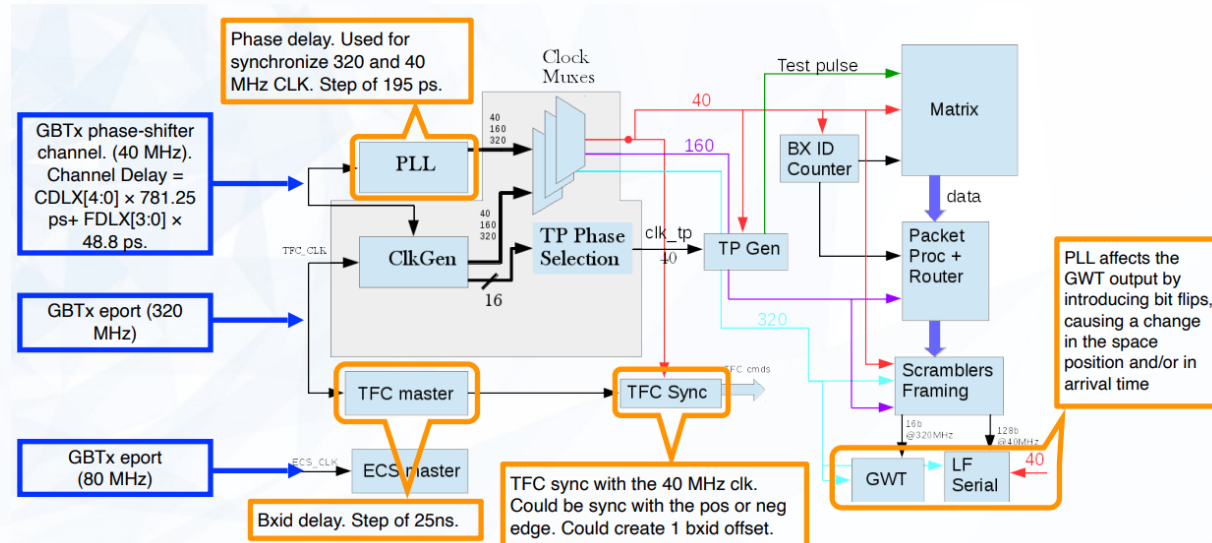


Improvement of Bxid spread

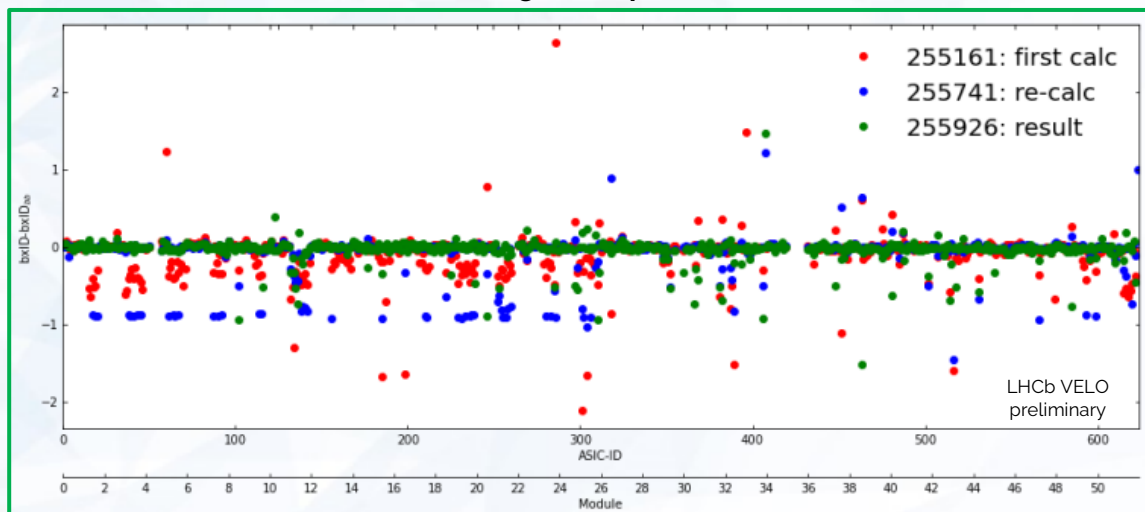


Time Alignment

- Time alignment depends on:
 - Control FPGA placed on surface.
 - GBTx and VeloPix clks
 - Time fast control (TFC) & 40 MHz clk sync.
- Multiple scan done to understand the detector behaviour.
 - PRBS test while scanning the PLL phase.
 - Coarse delay scan on the GBTx.
 - Scan of the sync of TFC with the 40 MHz clk.

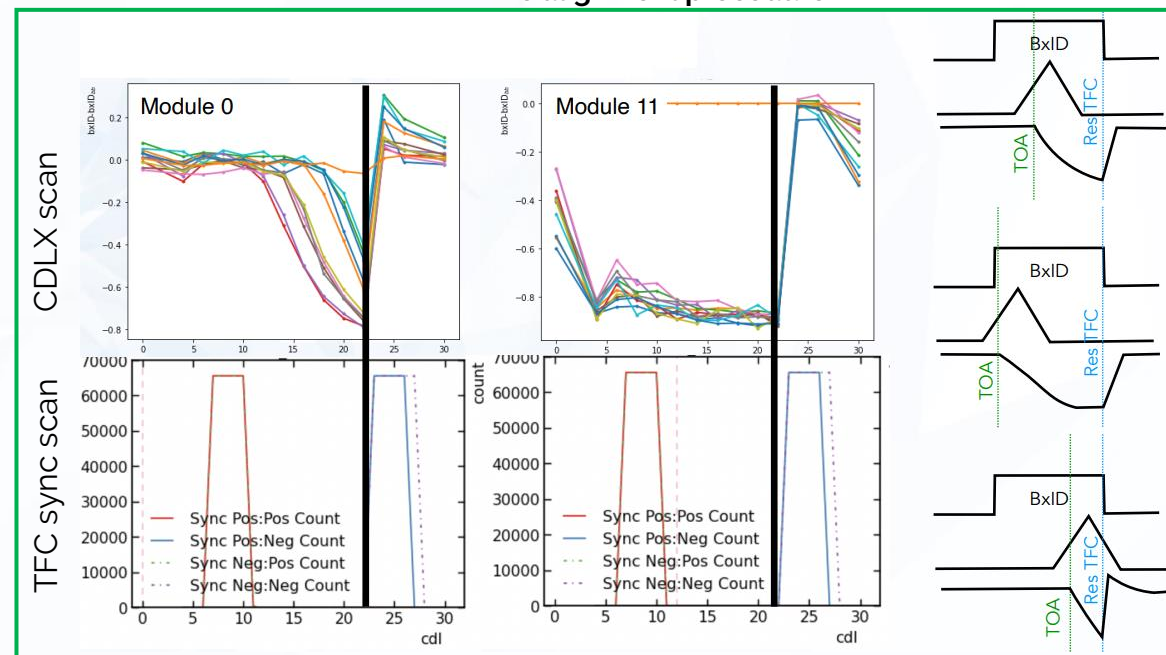


Time alignment performed



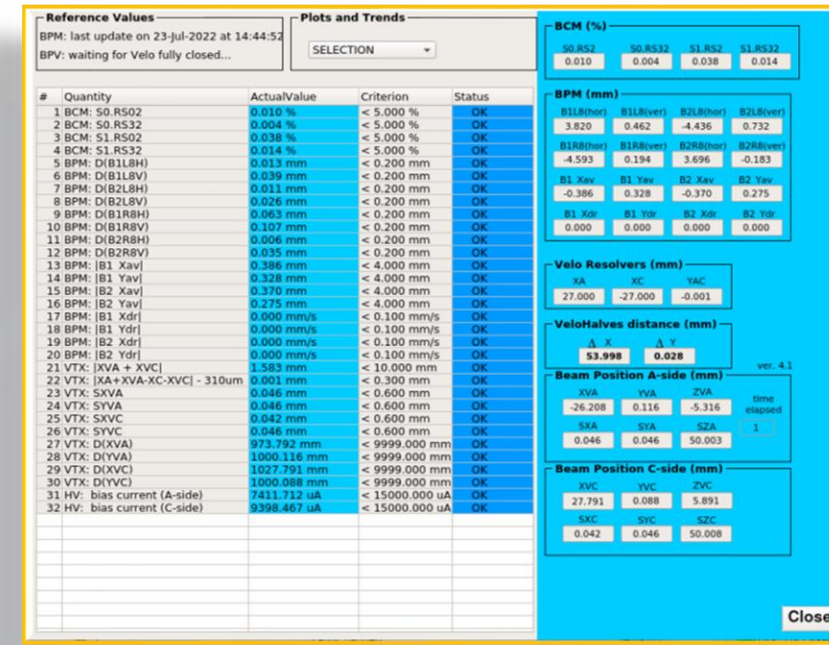
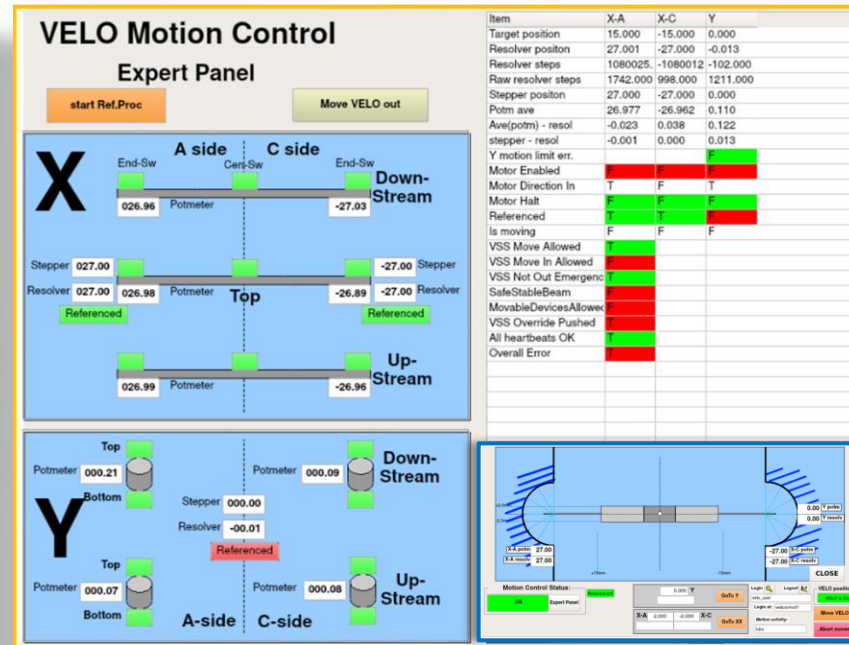
Fraction of bad chips :Total: 5.8%. A side: 8.0%. C side 3.5%
 Fraction of out of-time chips: Total: 2.7%. A side: 4.2%. C side 1.3%

Time alignment procedure

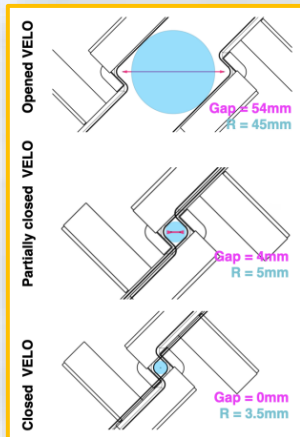


VELO Closing

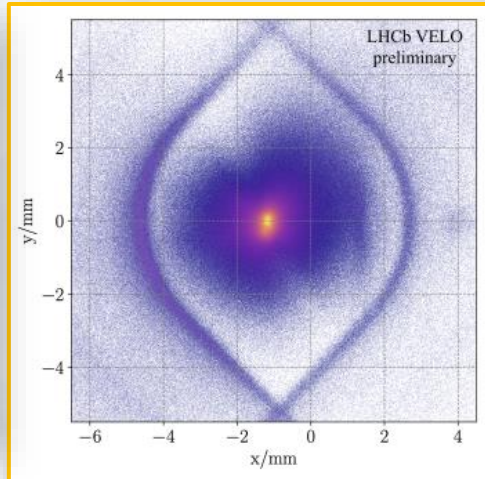
- Closing is based in the Primary Vertex reconstruction from the detector.
- Multiple criteria need to be satisfied: VSS, stable beam, FPGA communication, Beam Conditions Monitors, Beam Position Monitors, HV current, ...
- RF foil reconstructed to proceed to the final closing.
- Increased number of colliding bunches to study the temperature and vacuum variation and validate the closing.



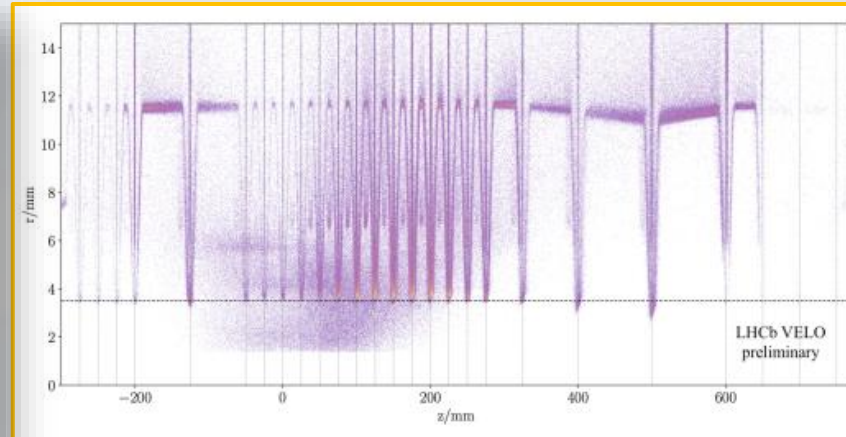
Closing Process



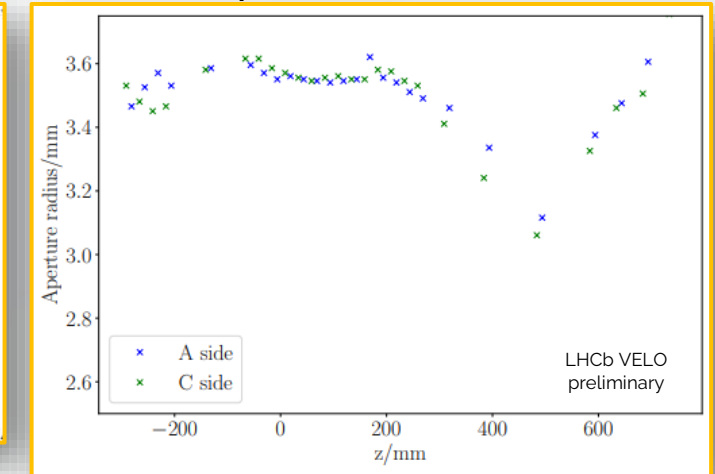
Z projection almost close



Z positions with vertex reconstruction

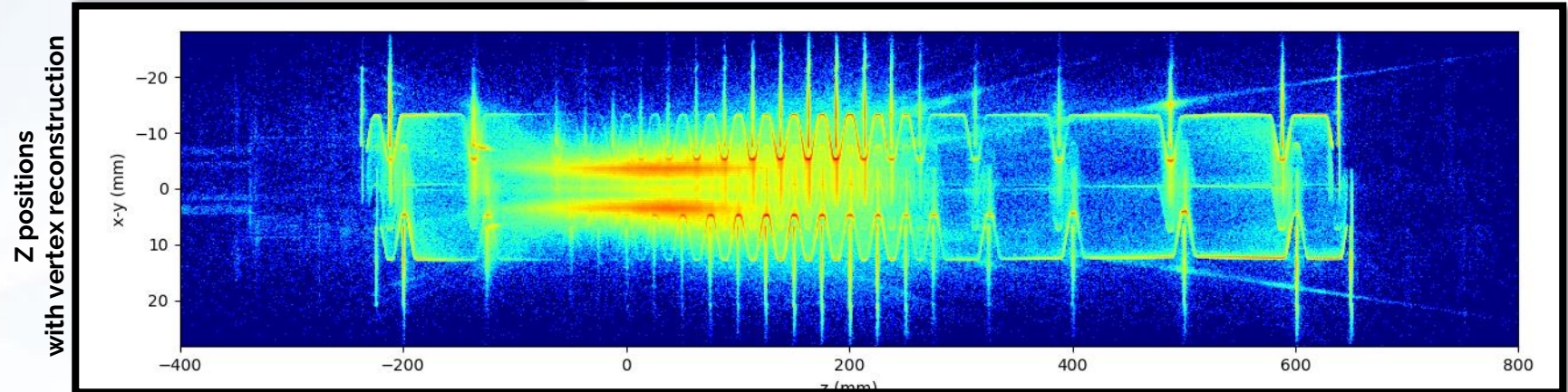
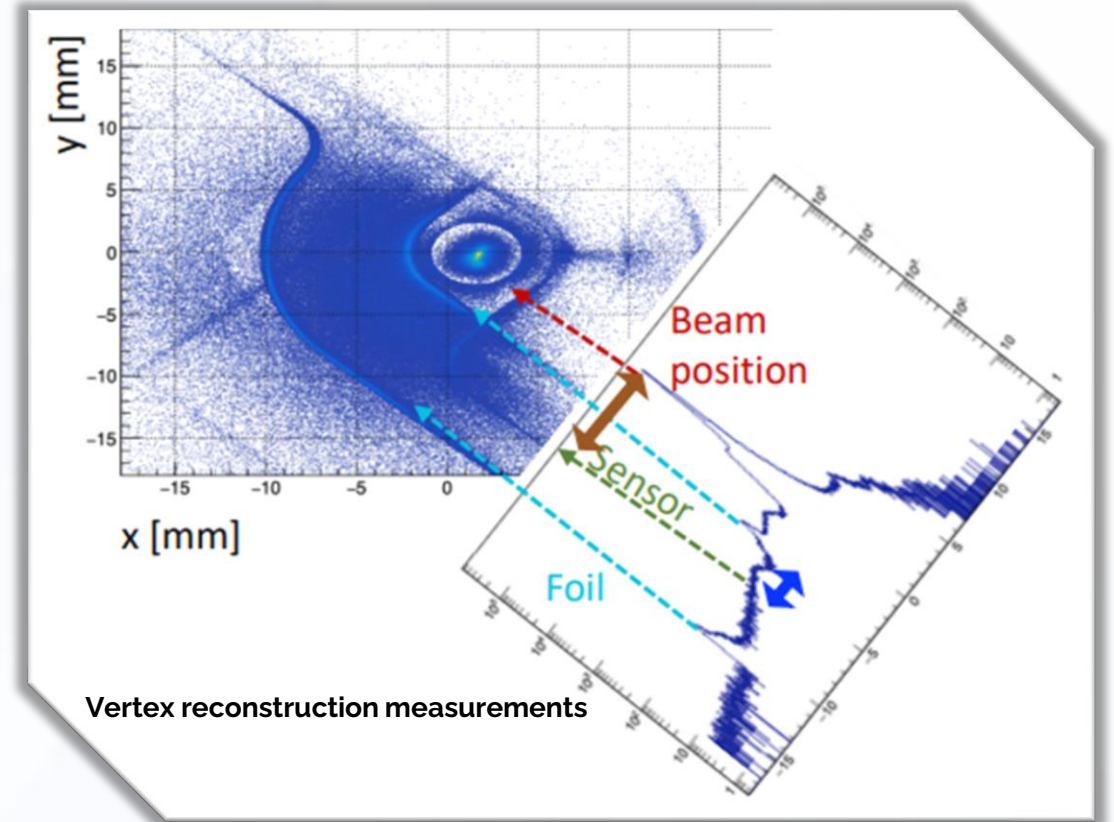
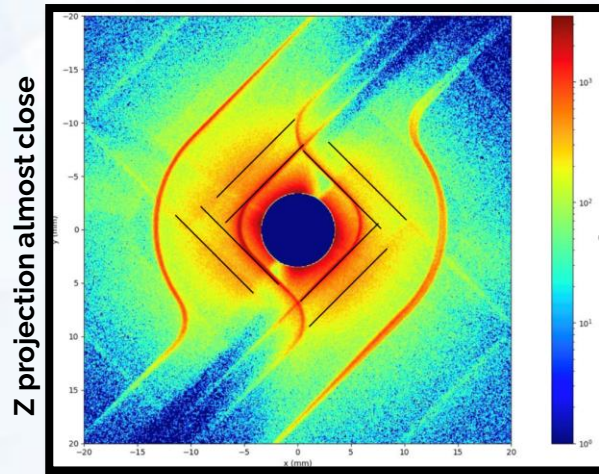


Aperture measurements



Vertex reconstruction

- One spacer was placed in each fixation point (3 per side) of the detector to the motion system to increase the clearance 1 mm.
- Vertex reconstruction measurement of module and RF foil position essential to be confident on removing the spacers.



DAQ and FPGA Clustering

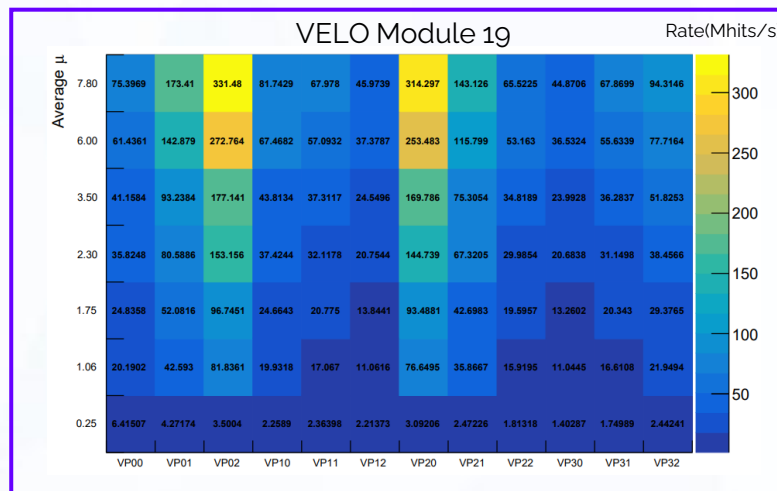
- VELO DAQ: 20 readout links at 5 Gb/s per module.
- Integrating the clustering in the FPGA.
 - 11% reduction of HLT1 reconstruction sequence.
 - O(50) less power consumption in the FPGA compare with the GPU.

[Phase I Upgrade of the Readout System of the Vertex Detector at the LHCb Experiment](#)

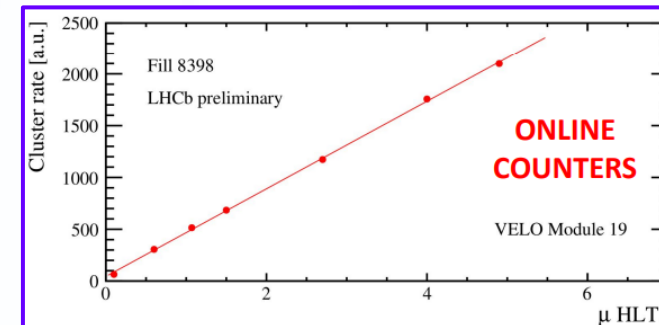
[Readout Firmware of the Vertex Locator for LHCb Run 3 and Beyond](#)

- μ (Number of collisions) scan in terms of VeloPix activity. Clusters and hit rate per VeloPix to measure luminosity.

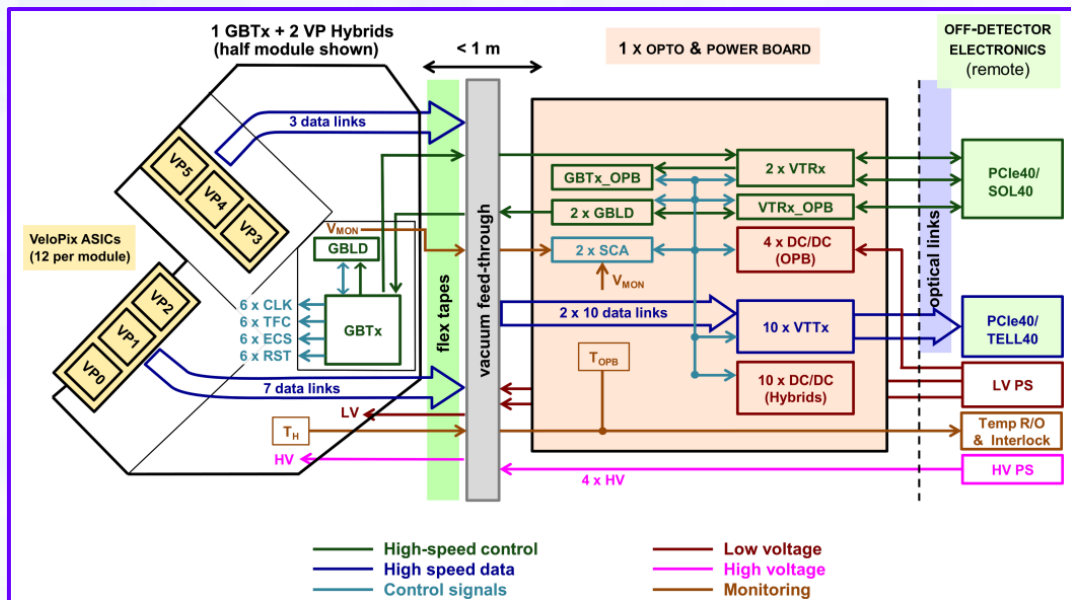
VeloPix Hit Rate



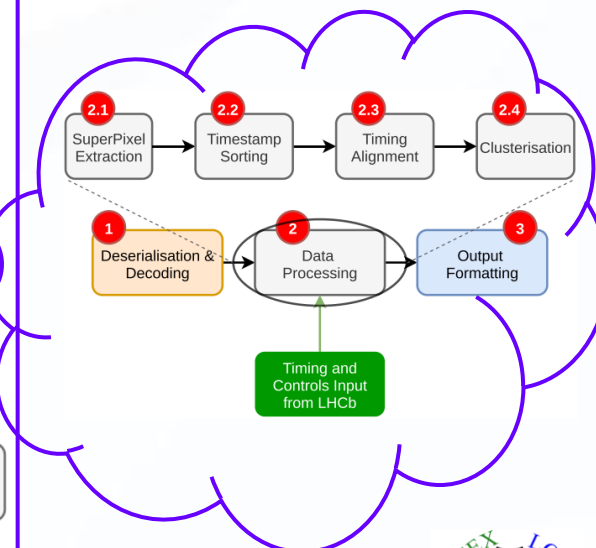
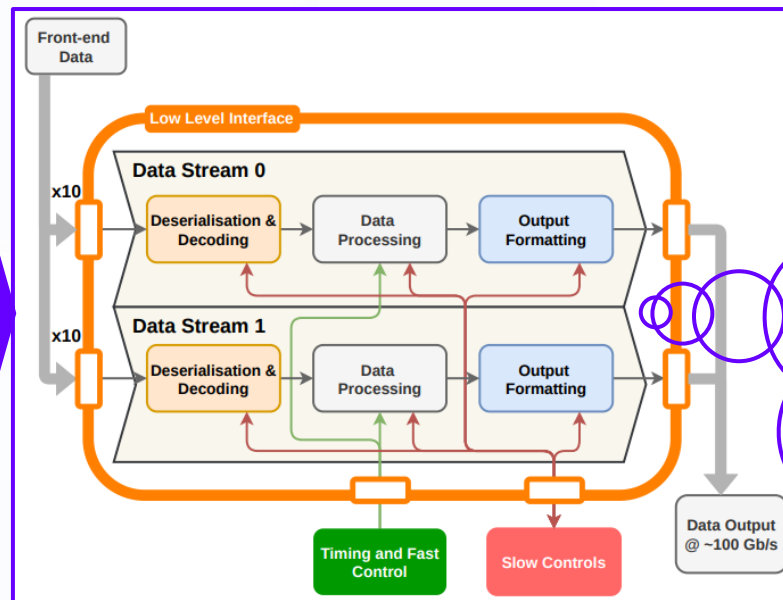
Clusters rate



Front end

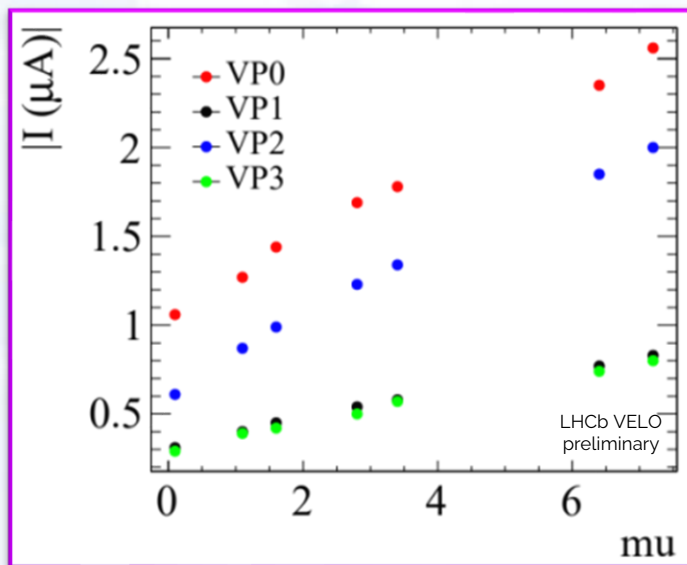


Back end

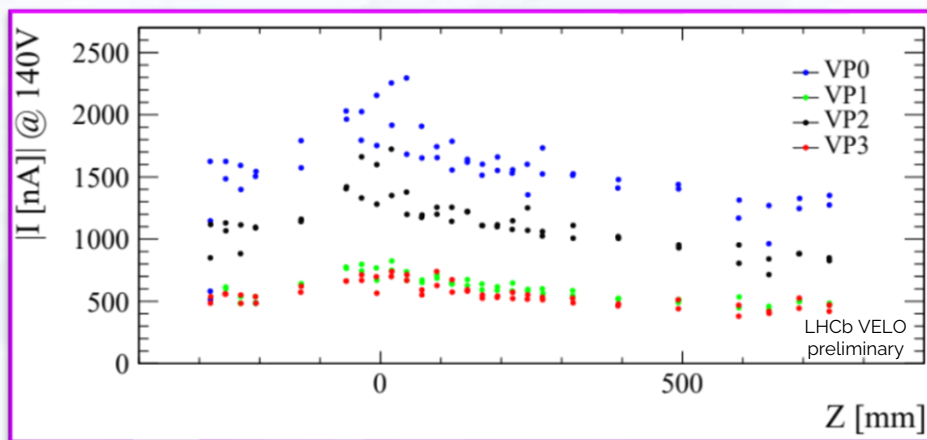


Leakage current evolution

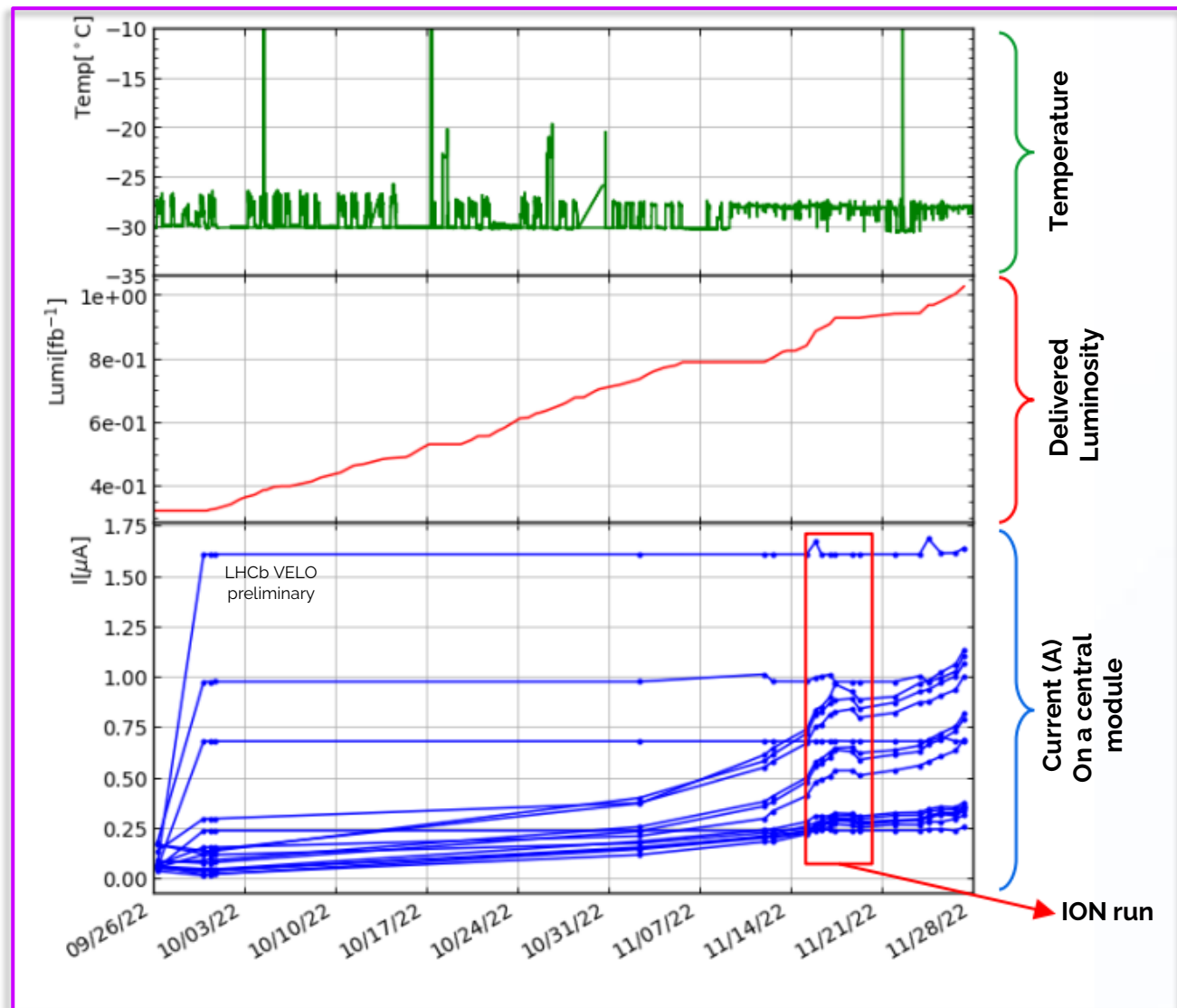
Multiplicity scan. Current increase linear



Leakage current vs Z position

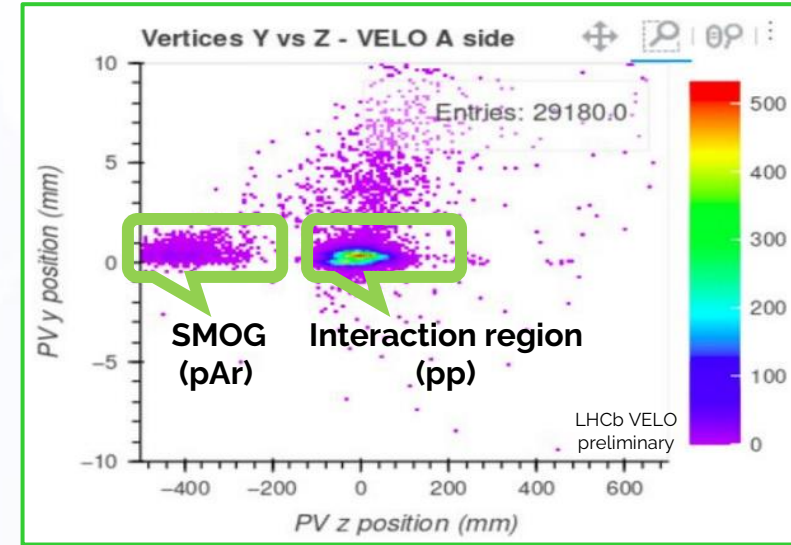
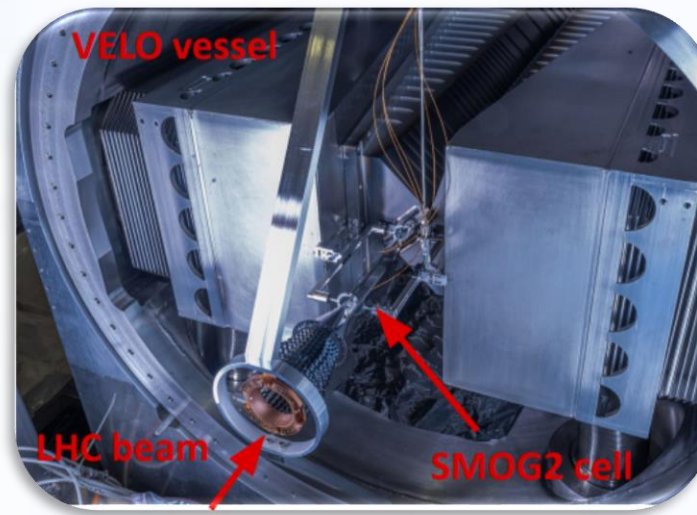


Current evolution in the last 2 months

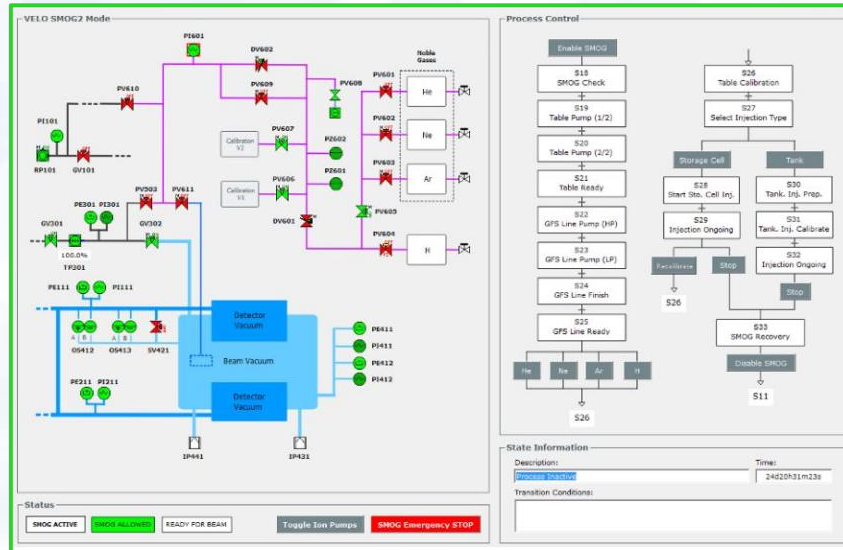


SMOG 2

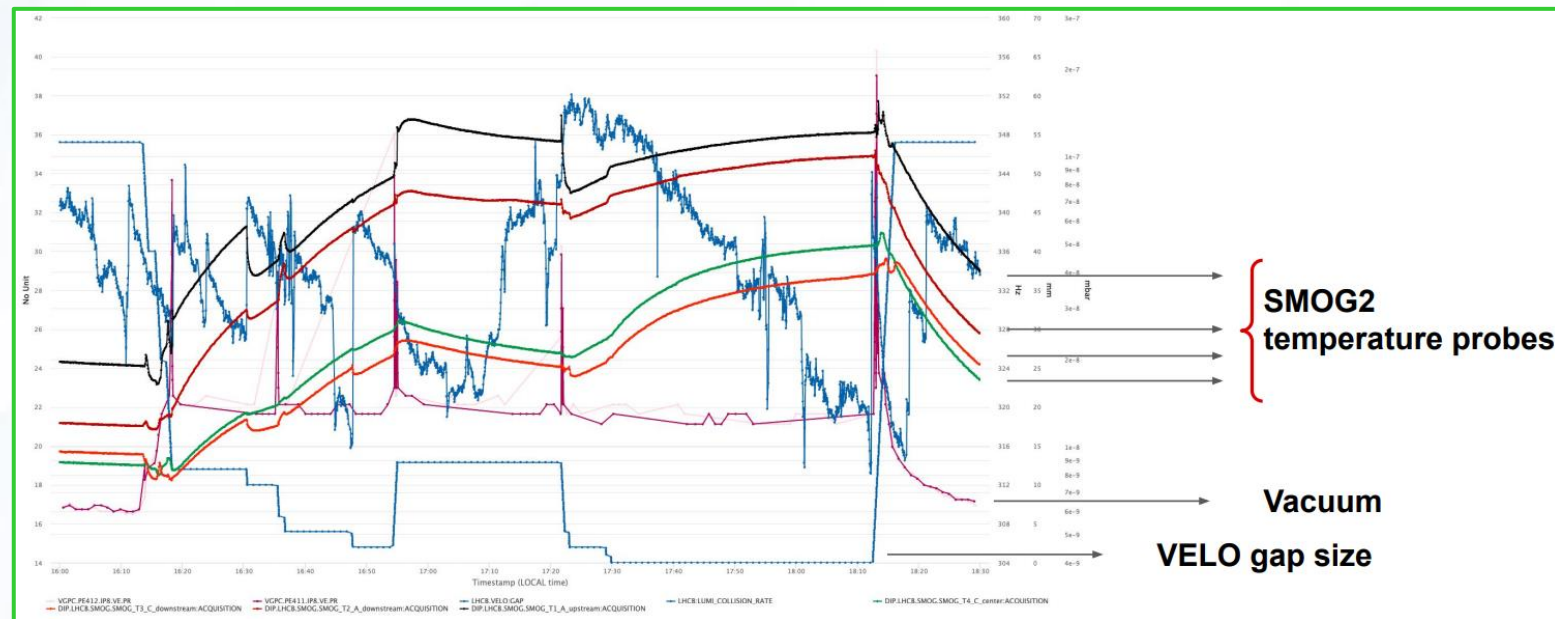
- SMOG 2 system inject gases (Ar, NE, He and H₂) in the LHC beam pipe, acting as the highest-energy fixed-target experiment. ([TDR](#), [Physics](#)).
- Gas feed system fully commissioning this year.



System control



Temperature, vacuum and VELO position



Conclusions

- Successful years of detector assembly and commissioned.
- Infrastructure systems (cooling, vacuum, LV, HV, motion, mechanics) properly working from first day.
- VeloPix tuned to get better performance.
- Time alignment performed with the full LHCb.
- Closing procedure stabilized and daily operational.
- First results on data rate and radiation damage.
- SMOG 2 system commissioning for fix target experiment.

*Looking forward for a successful
commissioning and data taking
year 2023*

