味物理讲座

2023年第 7 期

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LHCb UT Tracker

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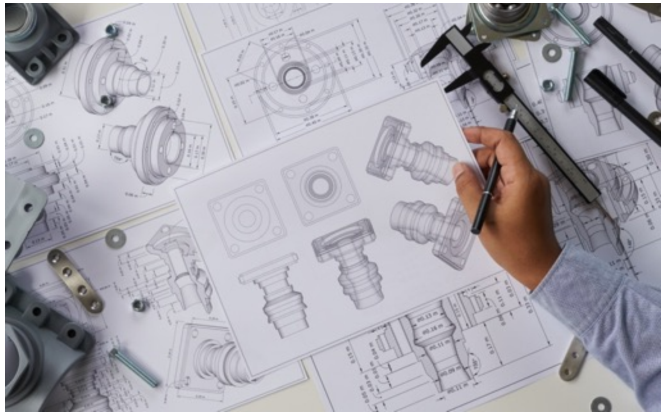
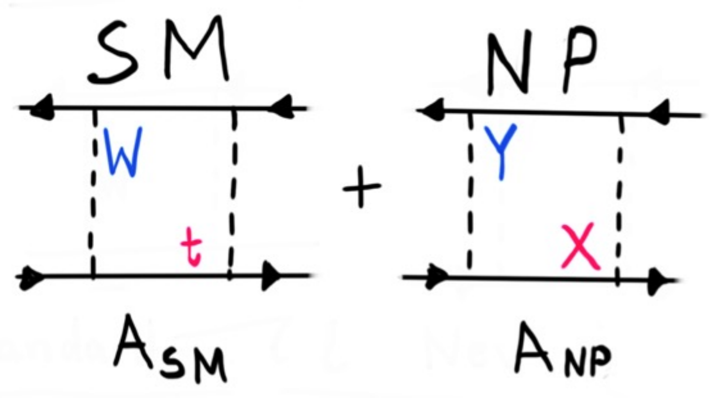
Outline

- ➢LHCb experiment
- ➢LHCb upgrades
  - ❑ Upgrade I
    Upgrade Ib
  - ❑ Upgrade II
- ➢LHCb UT detector
- ➢Summary



Focus on mechanical in this talk

Flavor physics road to New Physics



LHCb located at Large Hadron Collider (LHC)

- Search for New Physics in b & c sectors

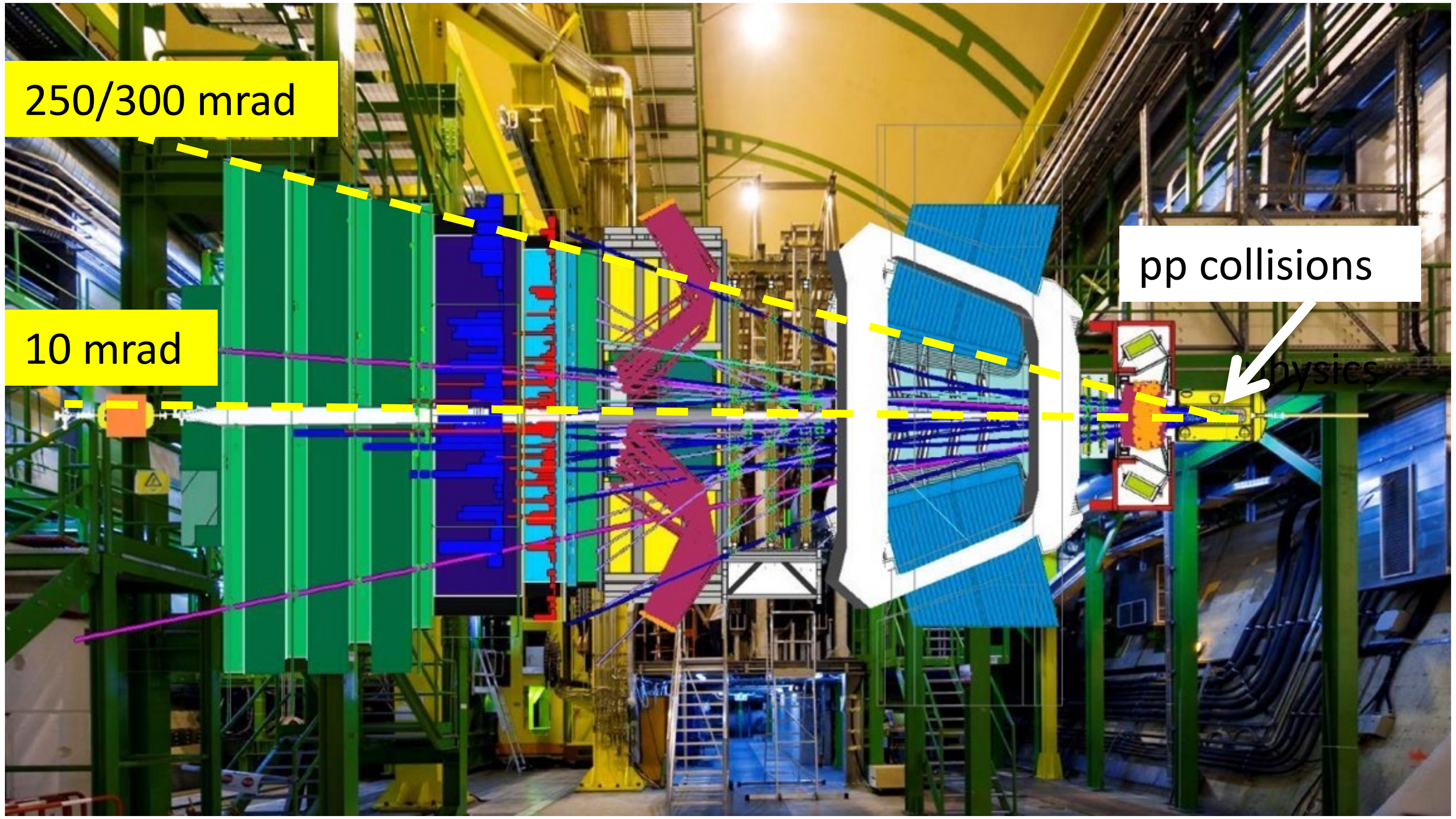
Sensitive to heavy particles in the loops

- Rare processes (suppressed or forbidden in SM)
  - $B^0_{(s)} \to \mu^+\mu^-$, LFV ...
- Observables with very small theoretical uncertainty
  - CKM angle γ, ϕ_s, $\Delta\Gamma_s$ ...

```
if res(Exp) != res(SM prediction){
  std::cout<<"NP found!"<<std::endl;
}
```

LHCb: a forward spectrometer @ LHC

Detector before 2019



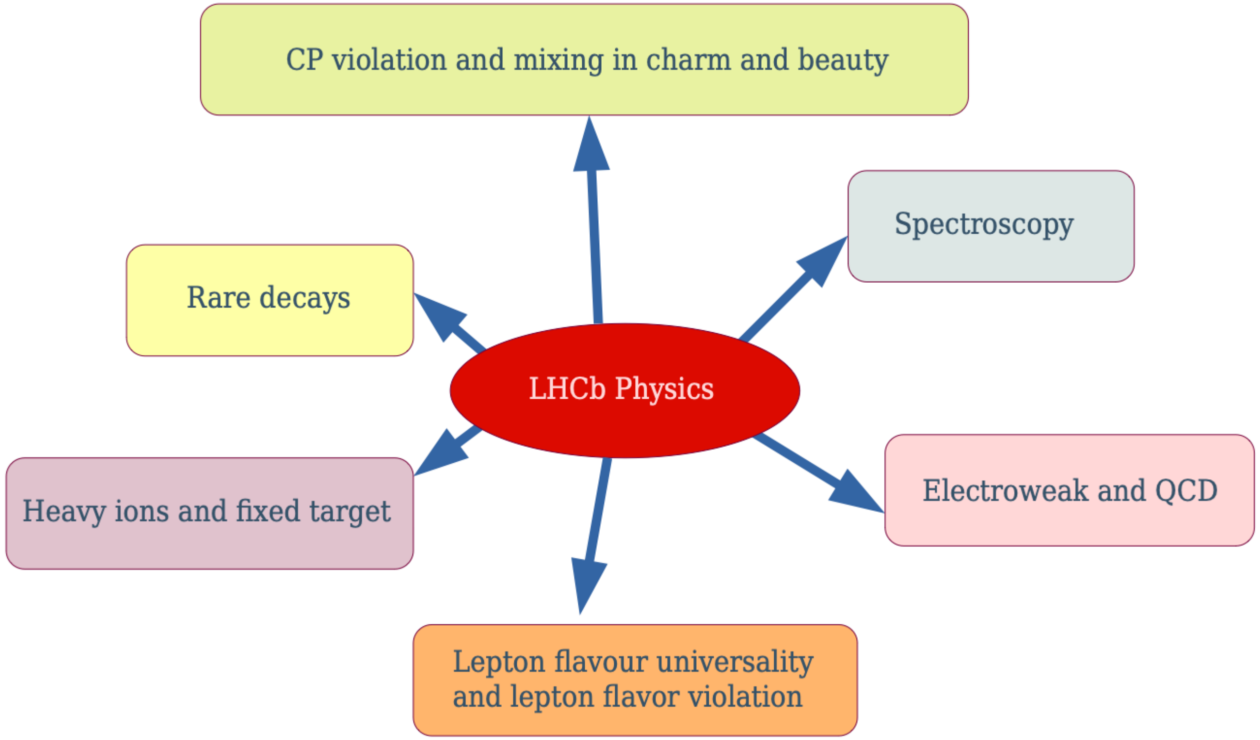
Main physics goal

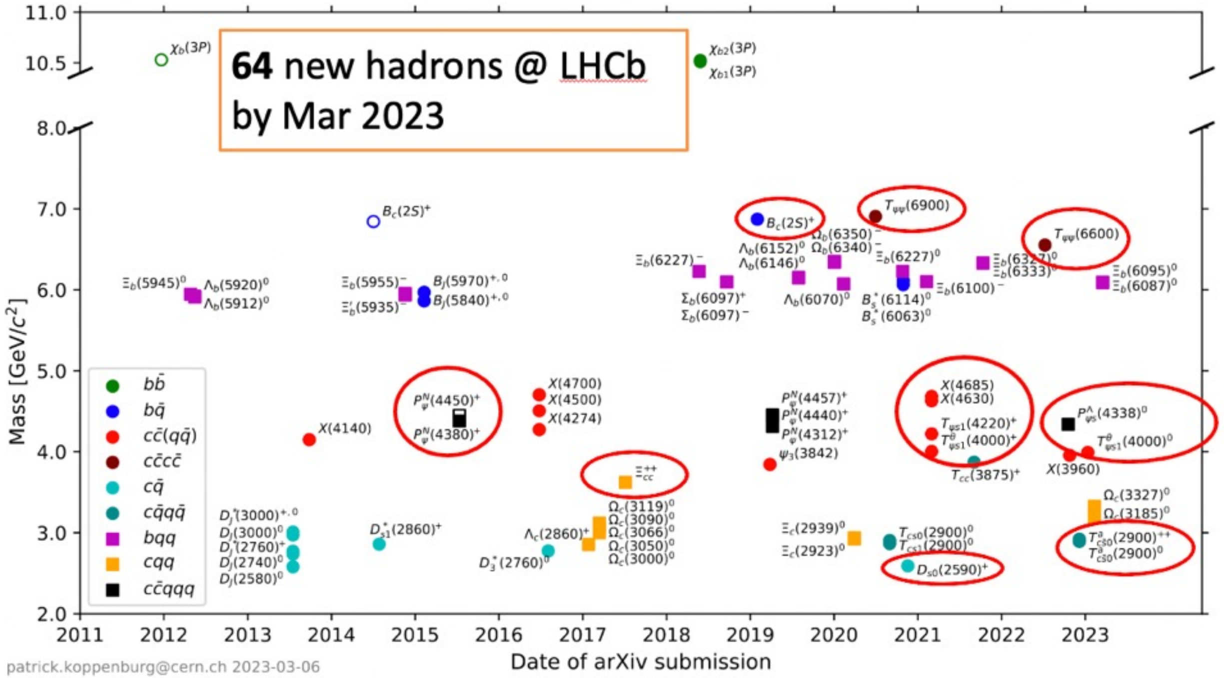
- To study b & c sectors on CP-voilation, rare dedays, search for new physics...

- $\Delta p/p = 0.5\%$ @ < 20 GeV/c, 1% @ < 200 GeV/c
- IP resolution ~ $15 + 29/p_T$ [GeV/c] μm
- Decay time resolution 45 fs ($B_s \to J/\psi\phi$)
- Kaon ID ~ 95% for 5% $\pi \to K$ mis-ID probability

LHCb physics performance in Run 1 & 2

A decade of important discoveries and precision measurements (9 fb^{-1} pp data)





- LHCb experiment
- LHCb upgrades
  - Upgrade I
  - Upgrade Ib
  - Upgrade II
- LHCb UT detector
- Summary

LHCb Upgrades

Upgrade I (U1), started in LS2 and to be completed in weeks:

$\mathcal{L}_{max}$~2x10^{33} cm^{-2}s^{-1}

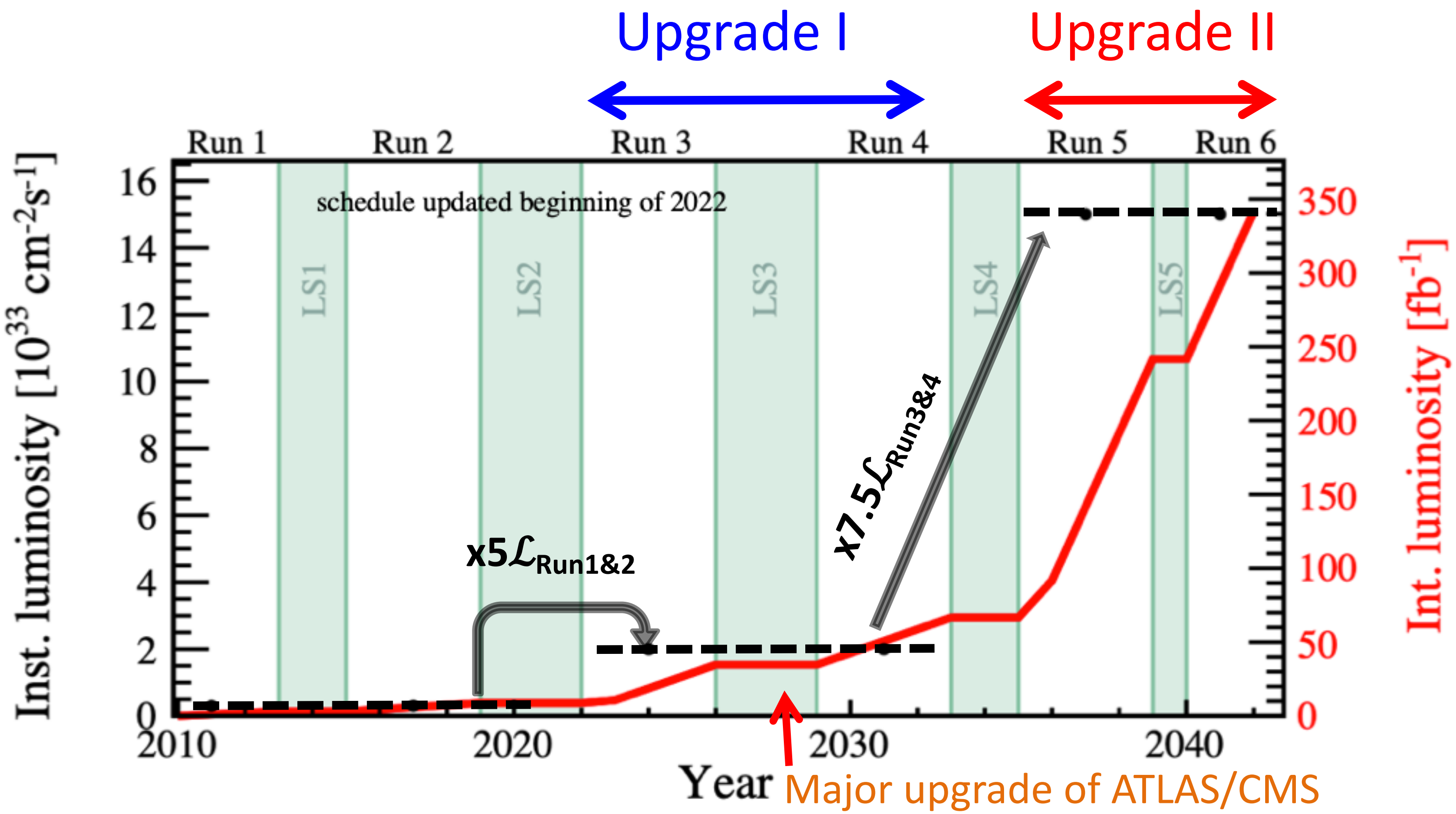
$\mathcal{L}_{int}$~50 fb^{-1}

Upgrade II (U2), starts after LS4

$\mathcal{L}_{max}$~1.5x10^{34} cm^{-2}s^{-1}

$\mathcal{L}_{int}$~300 fb^{-1}

Some smaller detector consolidation and enhancements in LS3 (2026) ⇦ U1b



Major upgrade of ATLAS/CMS

LHCb also plan enhancements (U1b)

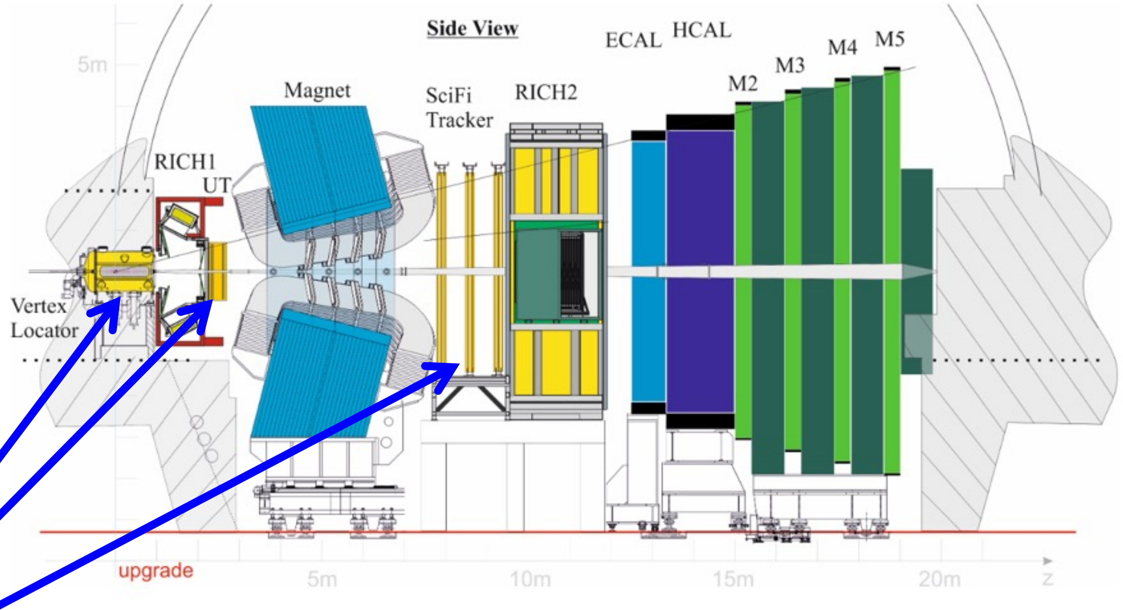
Upgrade I

Higher luminosity (5x$\mathcal{L}_{\text{Run1\&2}}$) results in

- ➢ Higher pile up, occupancy, fluence

No hardware trigger

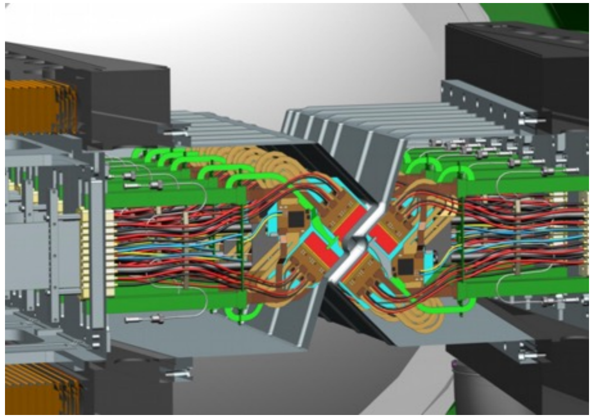
- ➢ GPU + CPU full software-based trigger
- ➢ Readout at the LHC bunch xing rate (40 MHz) for all subdetectors



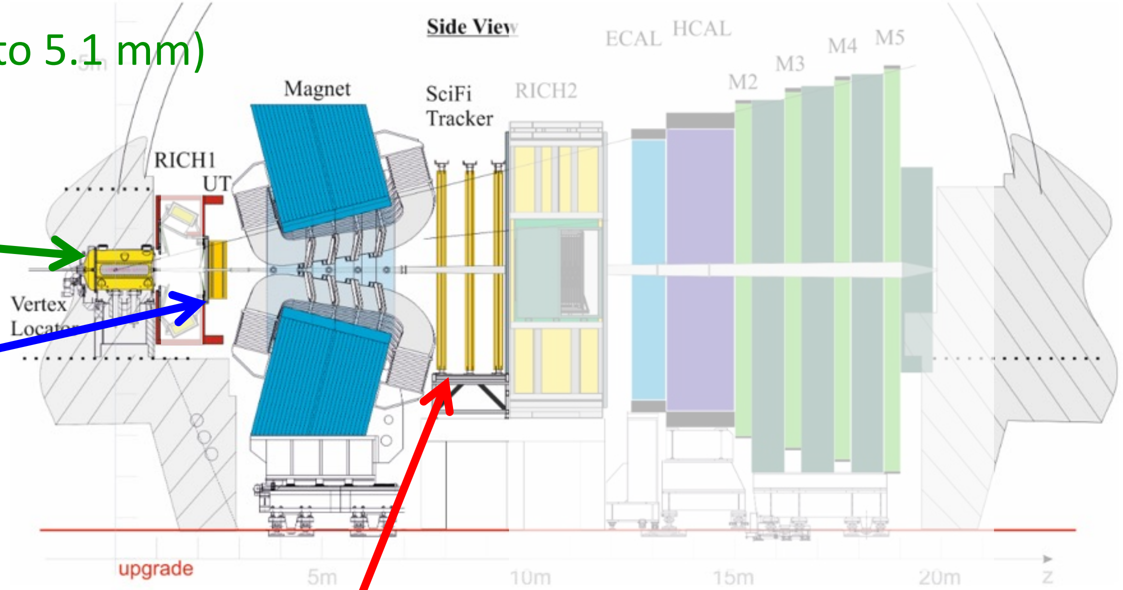
New tracking system

- ➢ **VE**rtex**LO**cator (VELO), **U**pstream **T**racker (UT) and **Sci**ntillating **Fi**ber Tracker (SciFi)

Upgraded trackers: VELO, UT and SciFi



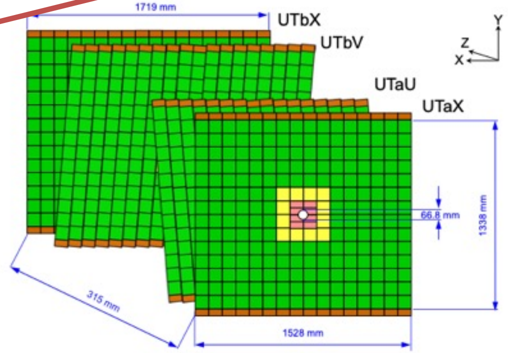
VELO: hybrid pixel detector
- Closer to the beam (from 8.2 mm to 5.1 mm)
- New RF box
- MAX fluence: 8×10^{15} $MeVn_{eq}cm^{-2}$



UT: Si Strip detector
- Higher coverage, segmentation, resolution
- Speed up tracks reconstruction & reduce $P_{GhostTrk}$...

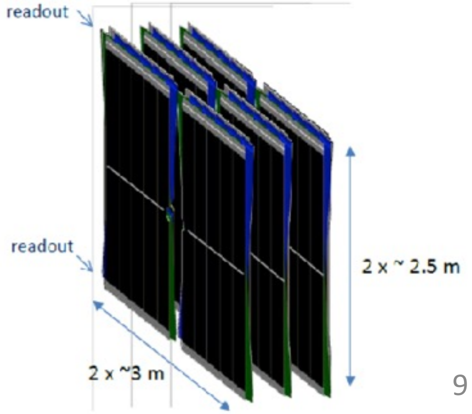
LHC... ...ibutes fro... ...ectronics, software to final installation

UT: more details later



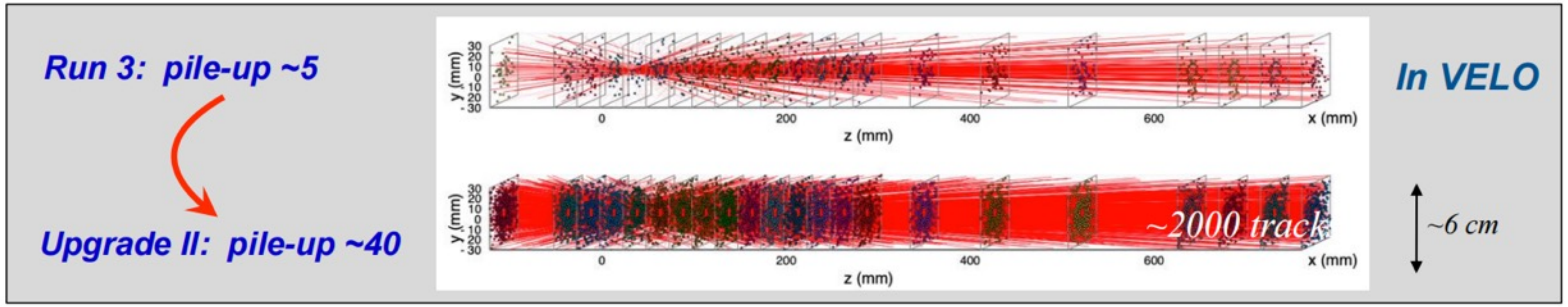
SciFi: Scintillating fibers detector
- 3 station with 4 detection layers
- 2x2.5 m long modules with Readout SiPMs at the outer edge

LHCb China group contributes PACIFIC R&D and production



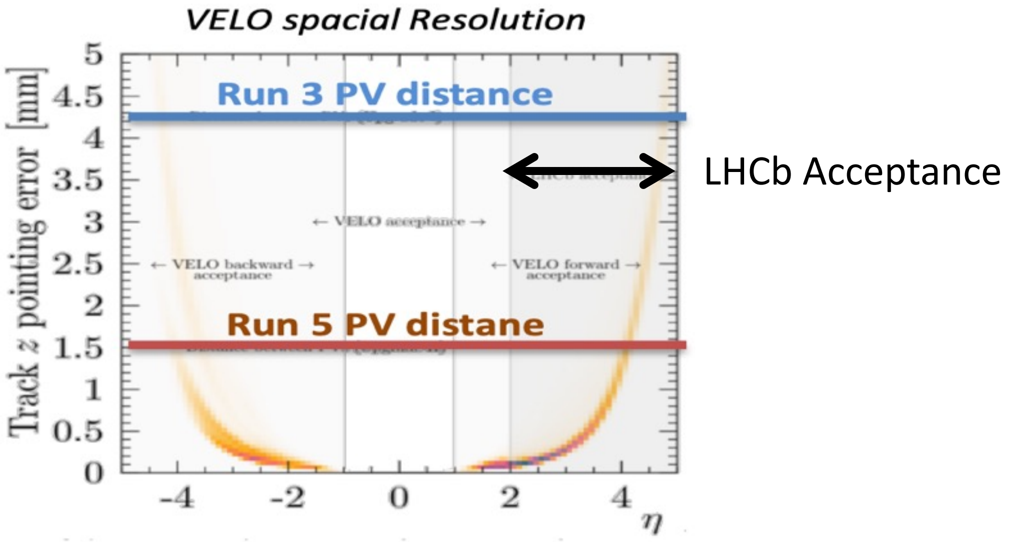
High pile-up in Upgrade II

In Upgrade II
$\mathcal{L}_{max}$~1.5x10^{34} cm^{-2}s^{-1}
$\mathcal{L}_{int}$~300 fb^{-1}
~ 40 visible interactions/Xing



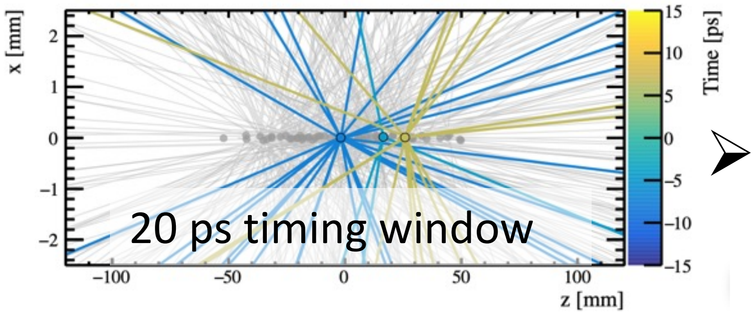
- High pile-up induces PV spacial separation of the same order as VELO resolution -> PV unresolvable
- Ensure $\varepsilon_{trigger}$ at high pileup condition

New detector with t information

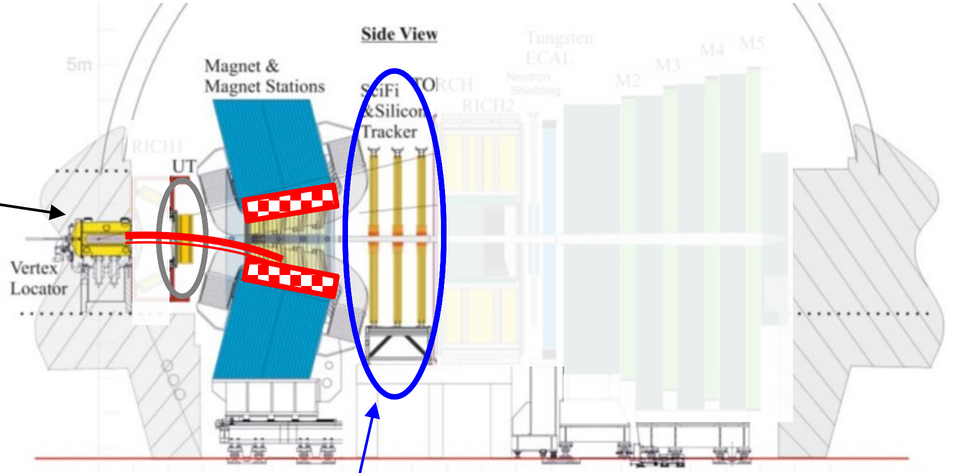


New tracking detectors in U2

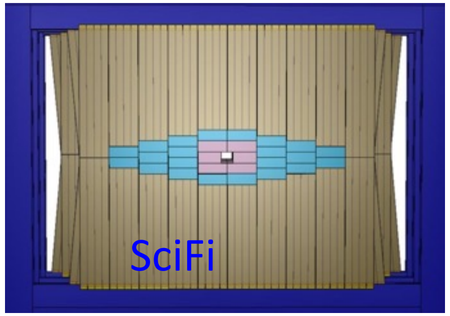
VELO: 4D detector with timing



➢ $\sigma_t(\text{Track}) = 20$ ps restores the performance to U1 level



UT: Pixel detector, more details later

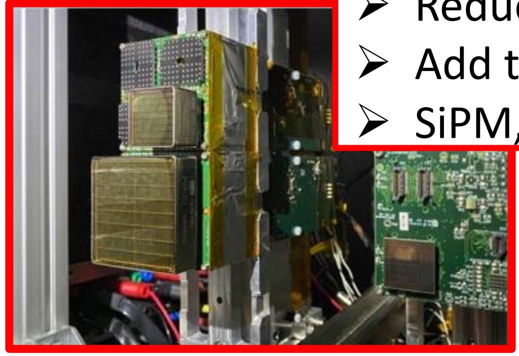


SciFi: Keep current design at outer region, while at most inner region CMOS sensors to be used

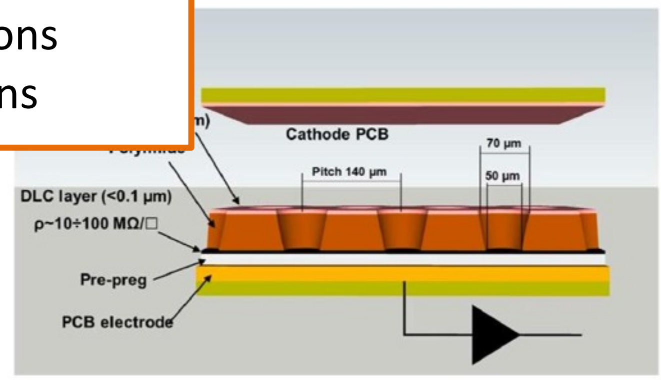
➢ New optical & cooling systems U1b @ 2026

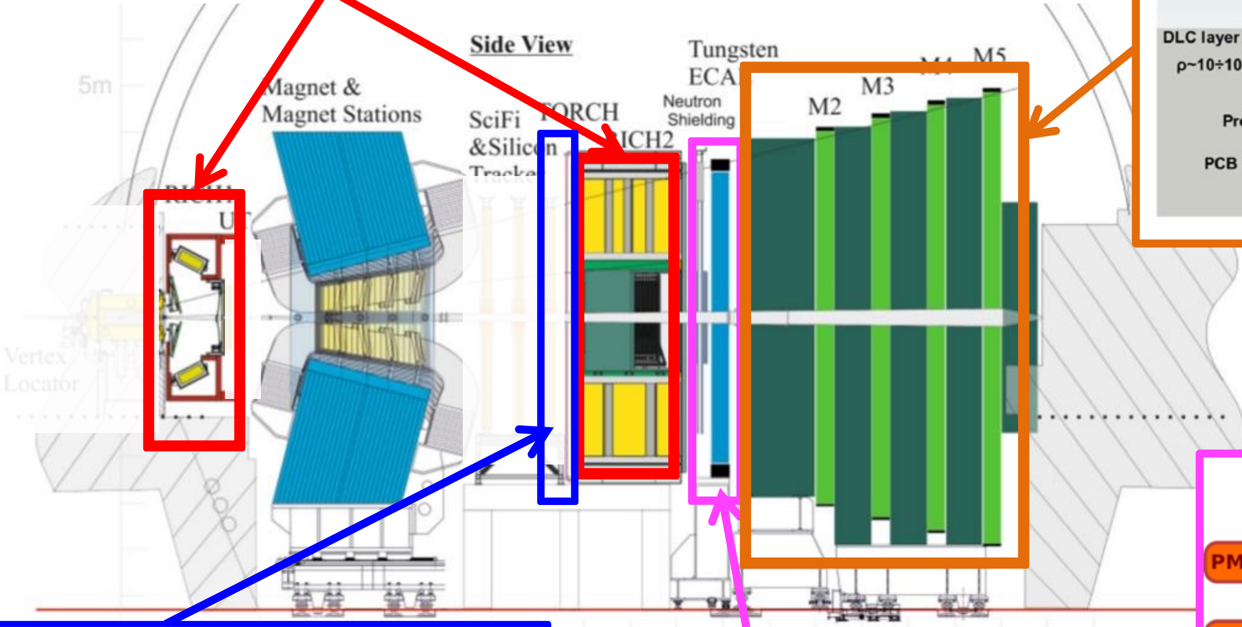
Particle Identification (PID) Detectors

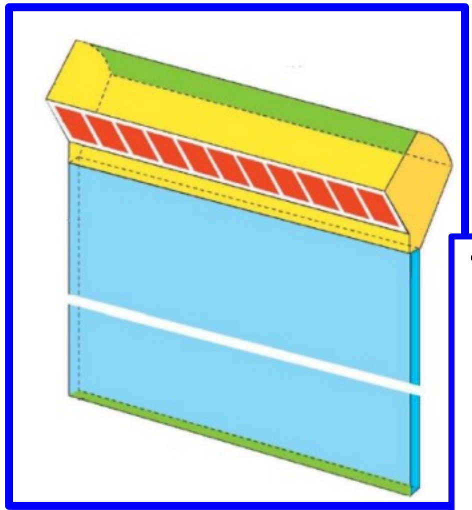
RICH1, RICH2
- Reduced pixel size
- Add timing information
- SiPM, MCP



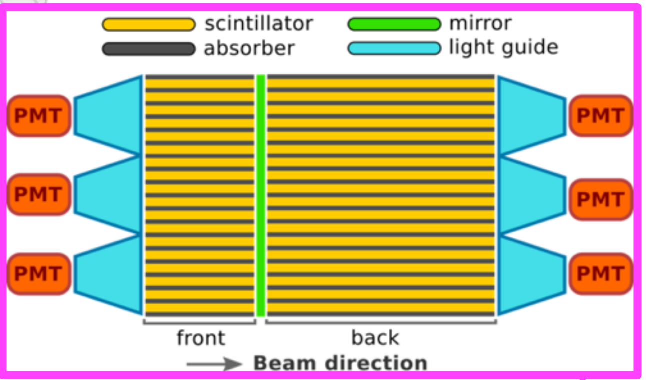
Muon
- μRWELL for inner regions
- MWPC for outer regions







TORCH
- To enhance PID capibilities for soft particles
- Measure light angle, path lenth and TOF



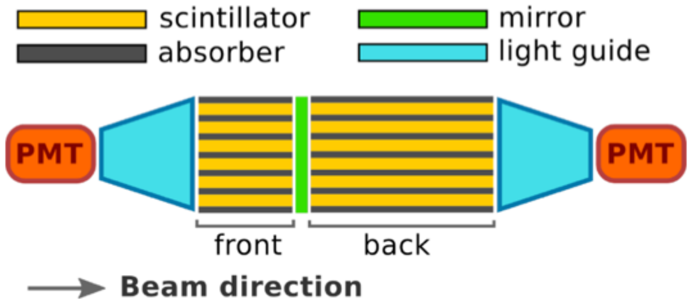
ECAL
- Space & time, longitudinal segmentation
- SPACAL with radiation hard crystals

5D calorimeter with precision timing

LHCb China groups are contributing

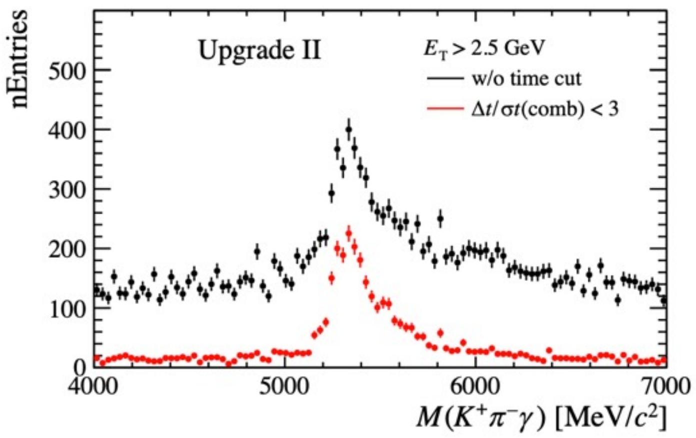
Key features: energy resolution ($10\%/\sqrt{E} \oplus 1\%$) , radiation hardness (up to 1 MGy), timing capability (tens of ps) and granularity.

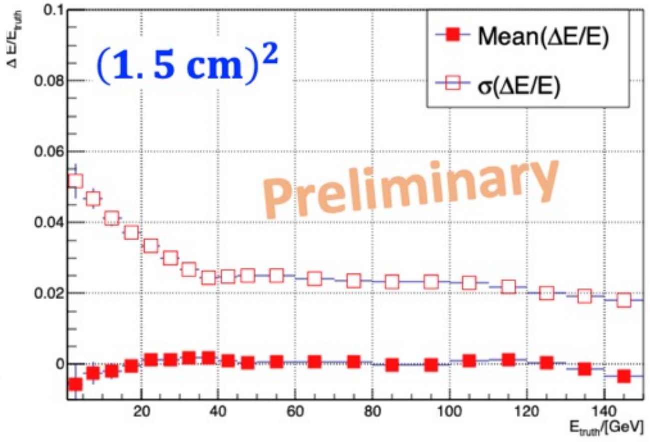
- ➢ Multiple technologies for different regions from inner to outer
- ➢ Possibility of adding timing layer: Si layers.
- ➢ Possibility of replacing the inner-most modules at LS3.

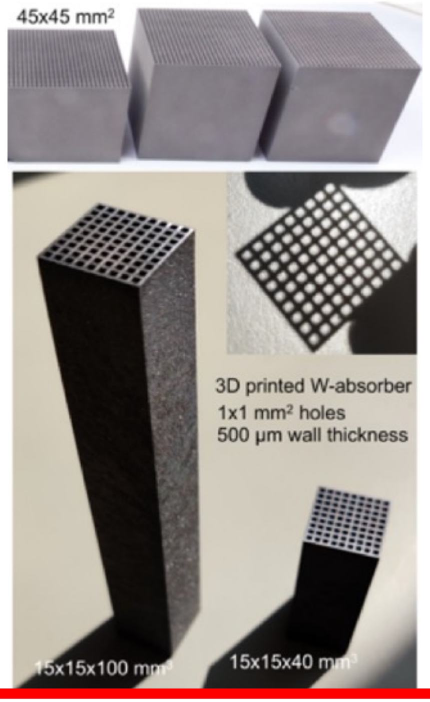


Significant contributions from LHCb China group

- ➢ Simulation studies
- ➢ Module production







Expected physics results @ LHCb Upgrade II

Key observables in flavor physics

Observable	Current LHCb (up to 9 fb^{-1})		Upgrade I (23 fb^{-1})	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})
CKM tests					
γ ($B \to DK$, *etc.*)	$4°$	[9, 10]	$1.5°$	$1°$	$0.35°$
ϕ_s ($B_s^0 \to J/\psi\phi$)	32 mrad	[8]	14 mrad	10 mrad	4 mrad
$\|V_{ub}\|/\|V_{cb}\|$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[29, 30]	3%	2%	1%
a_{sl}^d ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
a_{sl}^s ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	33×10^{-4}	[35]	10×10^{-4}	7×10^{-4}	3×10^{-4}
Charm					
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	[5]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5}	[38]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K_S^0\pi^+\pi^-$)	18×10^{-5}	[37]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare Decays					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	69%	[40, 41]	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—		—	—	0.2
$A_{\text{T}}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
A_{T}^{Im} ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$\mathcal{A}_{\phi\gamma}^{\Delta\Gamma}(B_s^0 \to \phi\gamma)$	$^{+0.41}_{-0.44}$	[51]	0.124	0.083	0.033
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	[51]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[53]	0.148	0.097	0.038
Lepton Universality Tests					
R_K ($B^+ \to K^+\ell^+\ell^-$)	0.044	[12]	0.025	0.017	0.007
R_{K^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.12	[61]	0.034	0.022	0.009
$R(D^*)$ ($B^0 \to D^{*-}\ell^+\nu_\ell$)	0.026	[62, 64]	0.007	0.005	0.002

LHCC-2021-012

Upgrade II will fully realize the flavor physics potential of the HL-LHC

Further pursue a broad physics programme

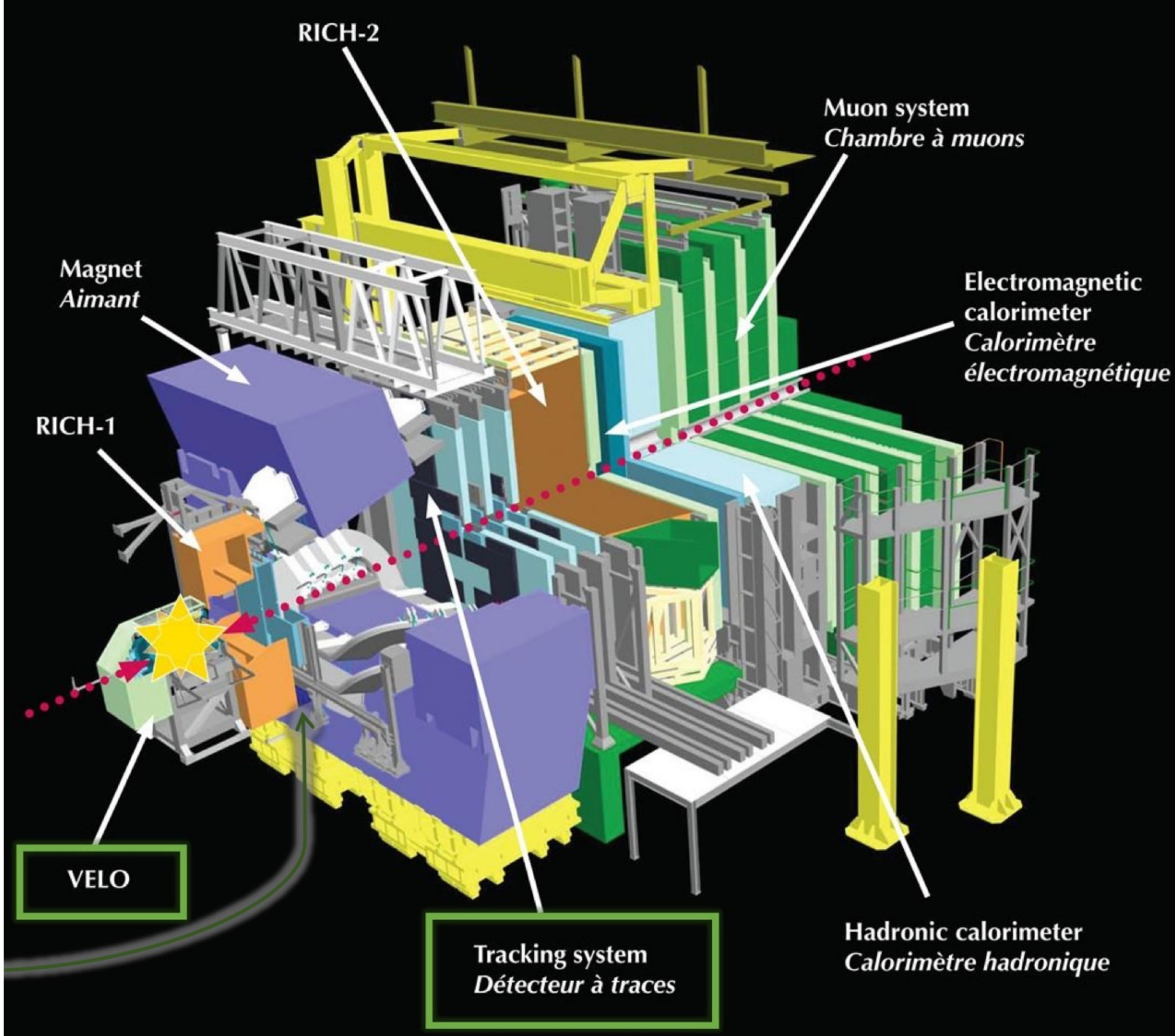
- Spectroscopy
- High precision EW and Higgs
- Dark sector
- Exotic search
- Heavy ions and fixed target

Success of the physics programme relies on

- HL-LHC providing LHCb ~ 50 fb^{-1}/year during Run 5&6
- A detector with similar or better performance as the present one for Run 3

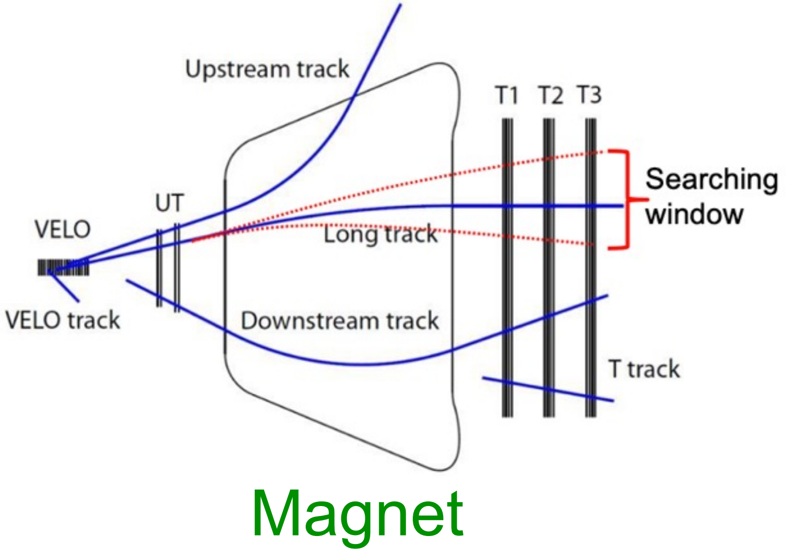
- LHCb experiment
- LHCb upgrades
  - Upgrade I
  - Upgrade Ib
  - Upgrade II
- **LHCb UT detector**
- Summary

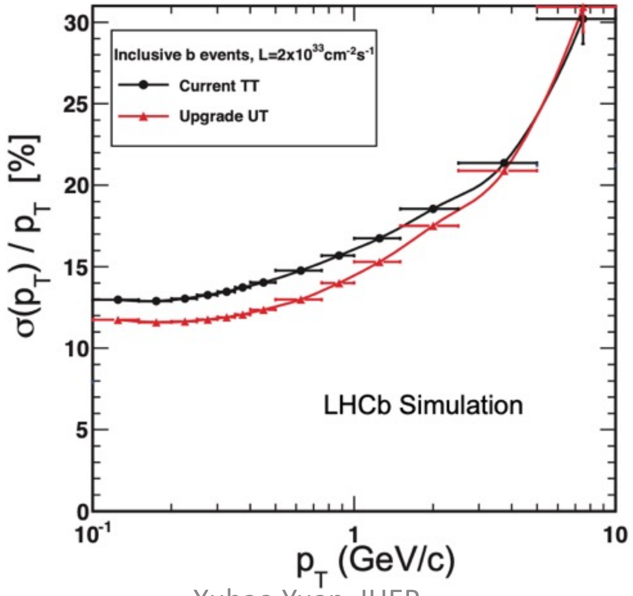
Location of UT

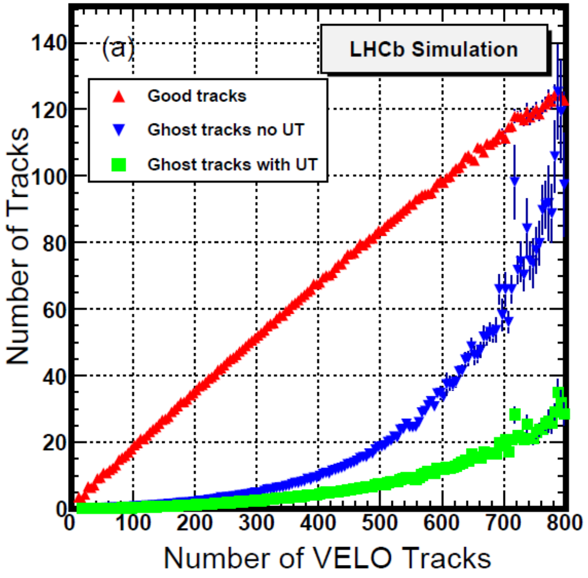


UT in LHCb tracking system

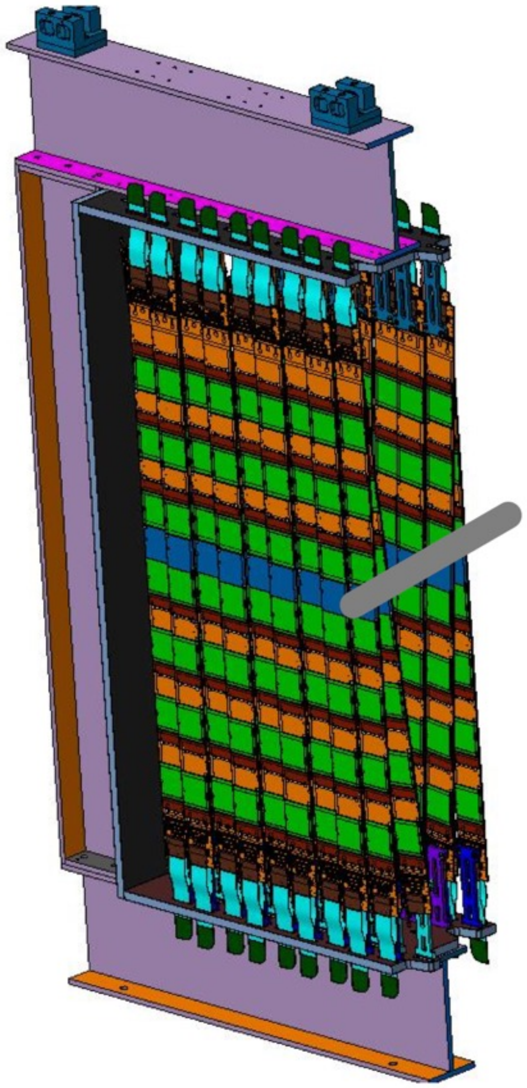
- Provide fast track reconstruction in software trigger
  - ❑ Searching window in SciFi tighten
  - ❑ Charge determined
- Reduce ghost rate in long tracks
- Increase reconstruction efficiency of long lived particles: e.g. $K_s^0 \rightarrow \pi^+\pi^-$, $\Lambda \rightarrow p\pi^-$

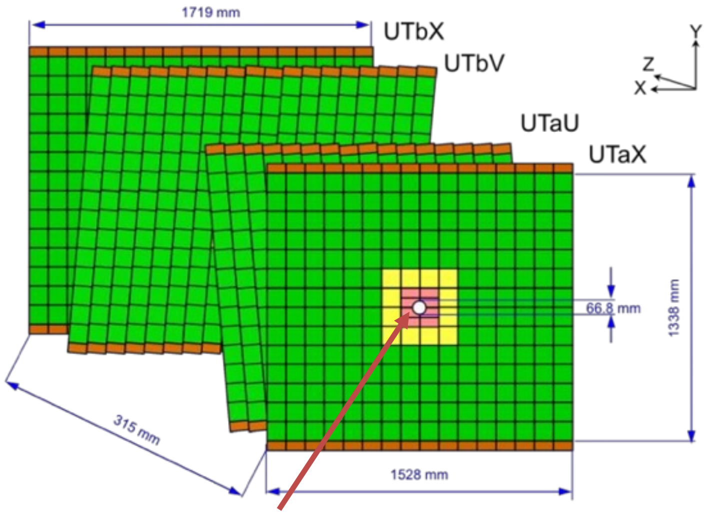






UT





Hole for beam pipe

Replace TT, similar geometric

- 4 layers (X, U, V, X) @ (0°,+5°,-5°, 0°), provide stereo measurements, precision horizontally

Higher segmentation, especially in central, <2% strip occupancy

Much improved coverage

- Circular hole surround beam pipe
- Sensor overlap in X&Y directions

Sensor more radiation resilience

- Φ_{max}~$5\times10^{14} n_{eq} cm^{-2}$ after 50 fb^{-1}
- Reduce material at small angle

40MHz readout SALT ASICs

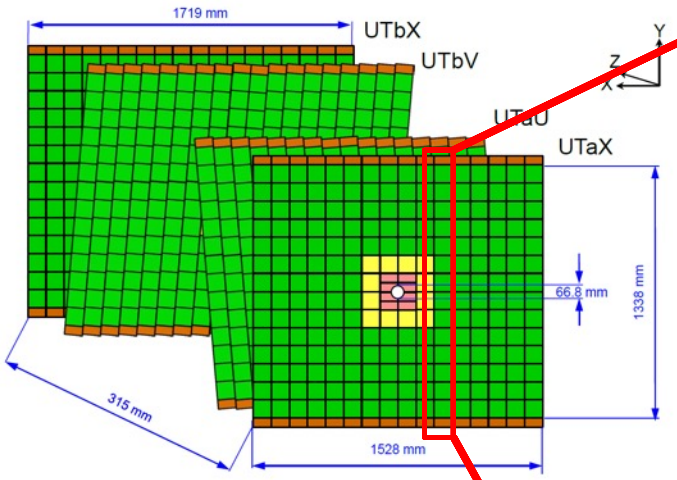
UT stave design

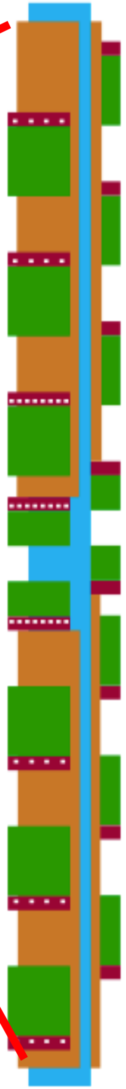
UT layers consist of Staves
- 16/16/18/18 staves on UT layers

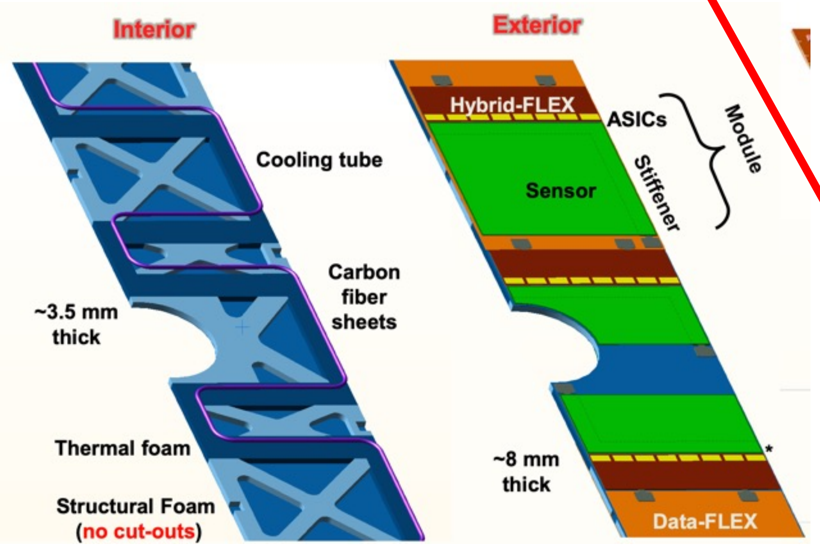
Stave:
- Main mechanical element of UT
  - Mounting & positioning for sensors
- Stiff sandwich structure of lightweight CFRP/foam
- Integrated with CO_2 cooling system

Components of fully-instrumented stave
- "Bare" stave + Dataflex + Modules

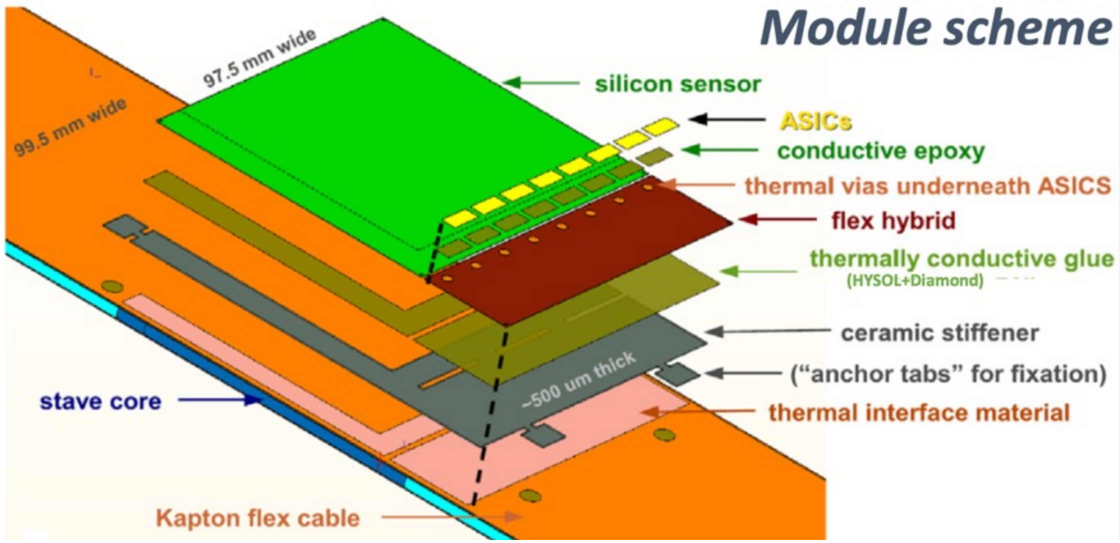
Adapting ATLAS-type integrated stave concept







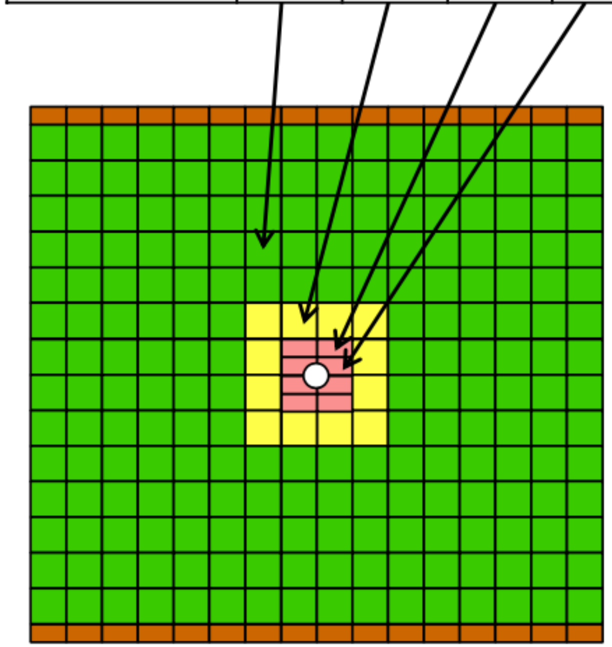
UT module



Basic detector unit

- Capture particle hits and processes signals
- No over-constrain sensor, allows for bow
- Reworkable epoxy(TIM)

Sensor	A	B	C	D
Pitch (μm)	187	94	94	94
Length (mm)	98	98	49	49
Strips/sensor	512	1024	1024	1024
Number	888	48	16	16



Four types of sensor:

A-type (~92%): p^+-in-n, 320 μm thick

Strip pitch 187 μm

B/C/D-type: n^+-in-p, 250 μm thick

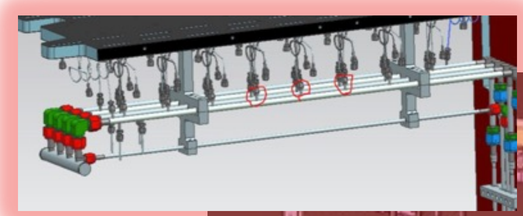
C&D-type: half length

Strip pitch 94 μm

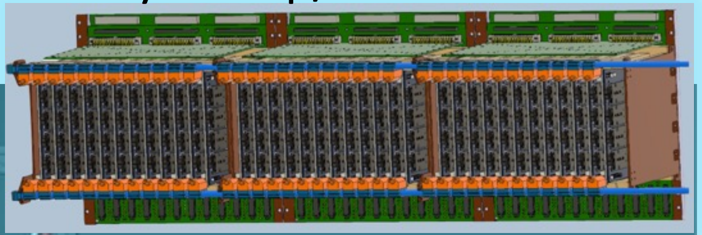
Finer granularity in central region

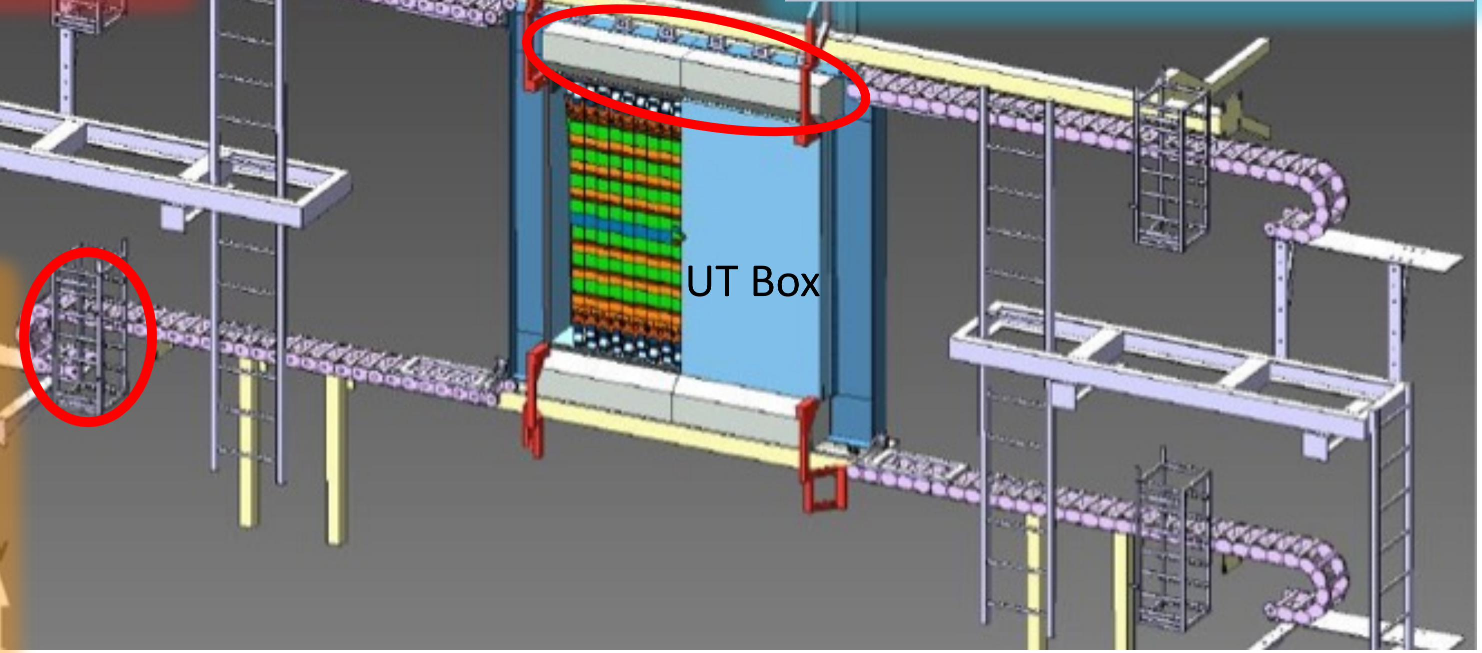
UT Integration

Staves cooled by CO_2, tested btw -30°C and 20°C



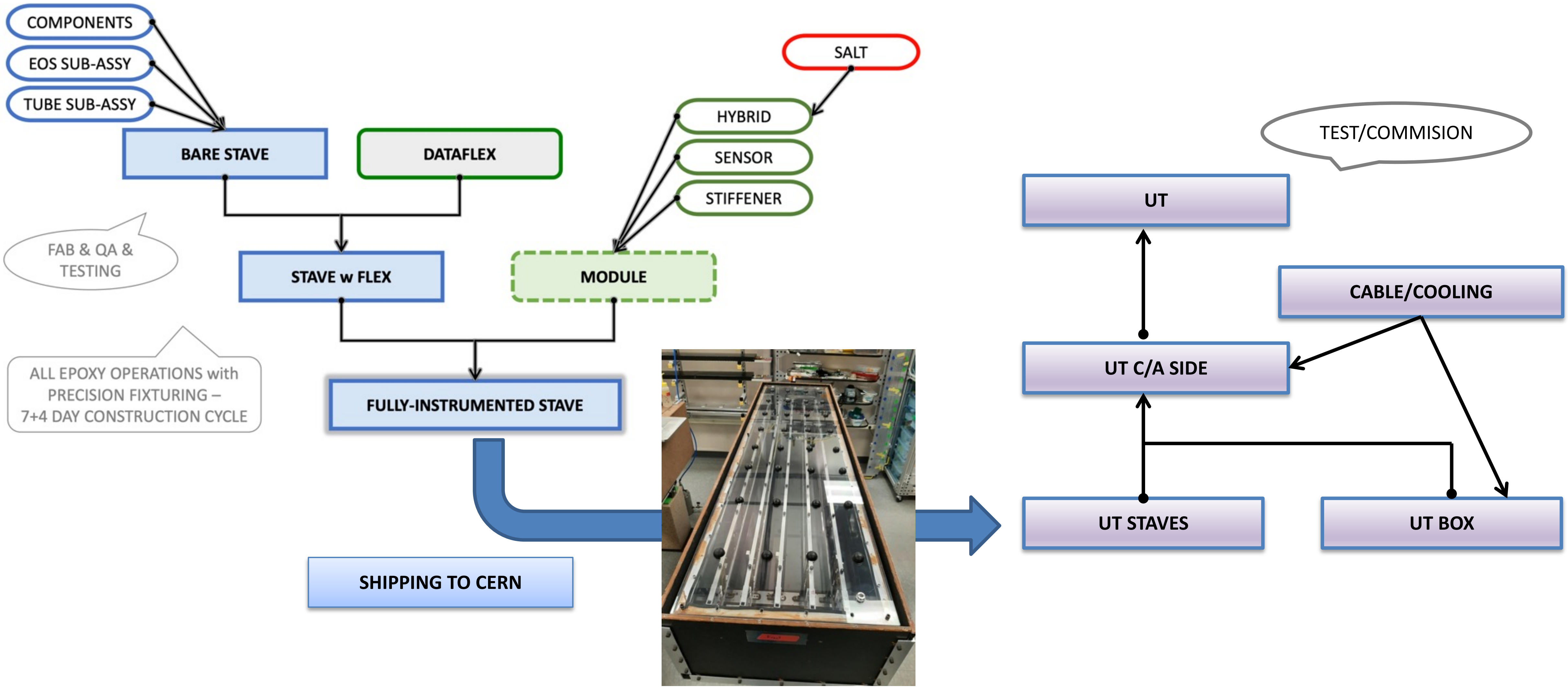
PEPI cooled by water, boxes sit directly on top/below staves



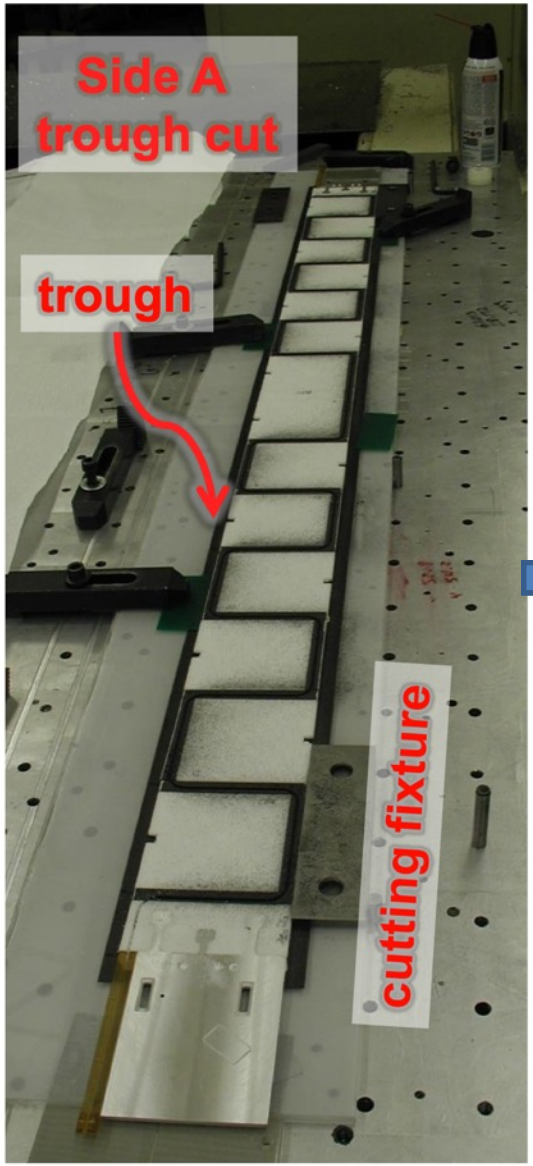


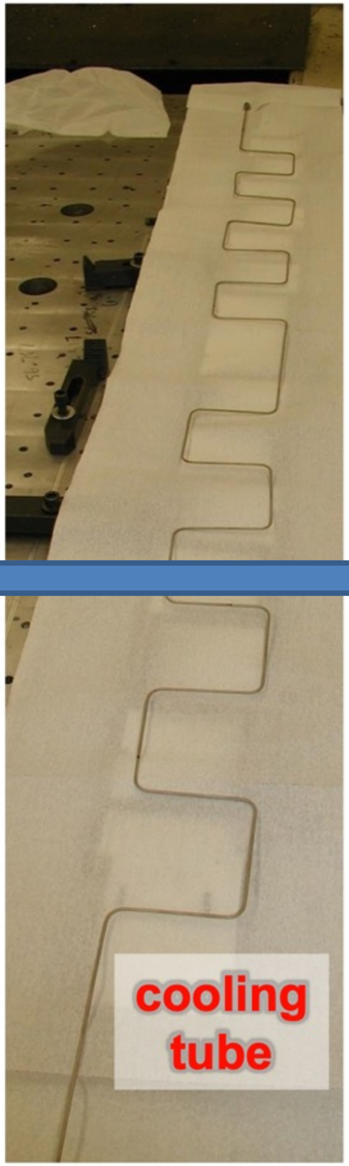
LV & HV regulation at service bays

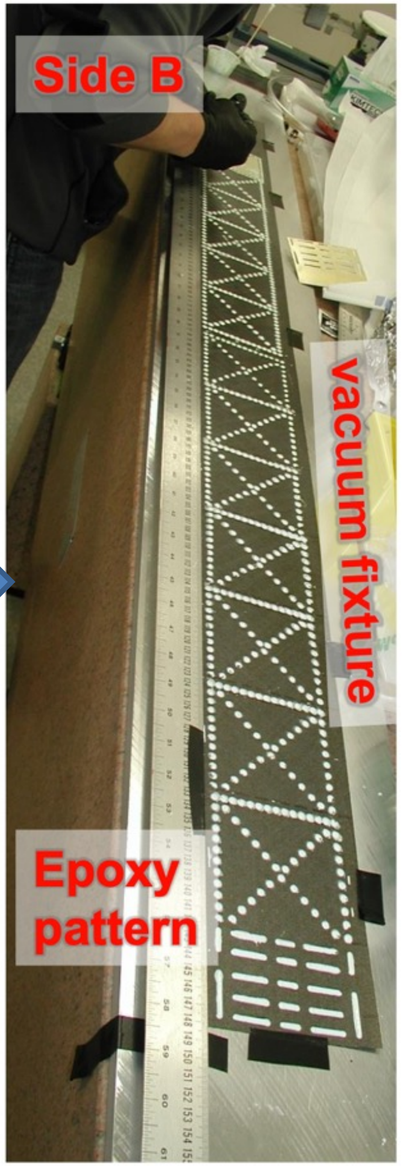
UT construction overview



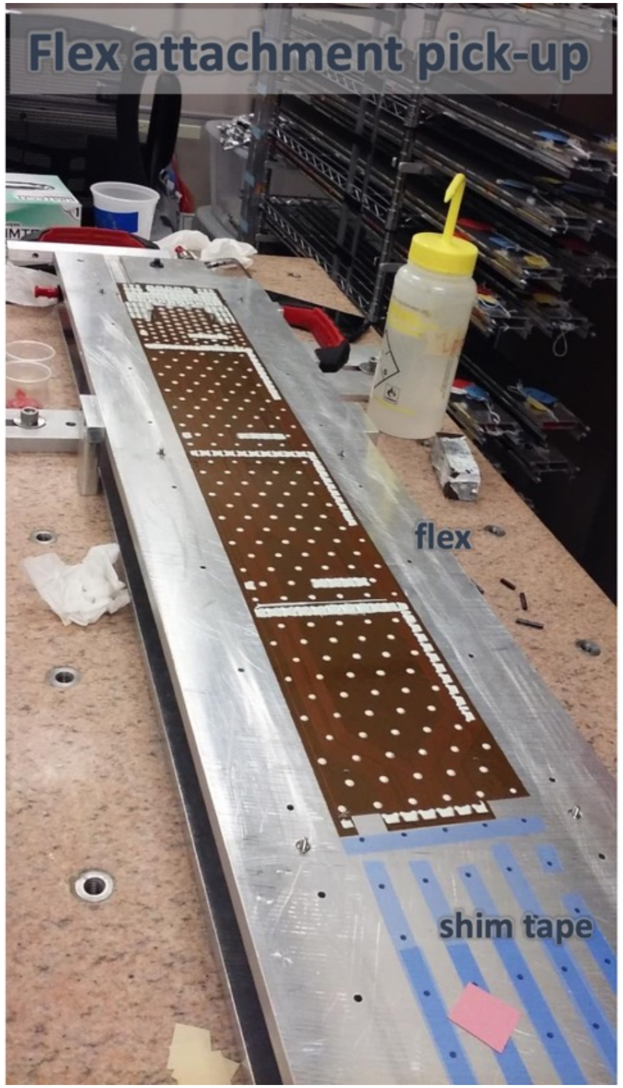
Bare stave construction

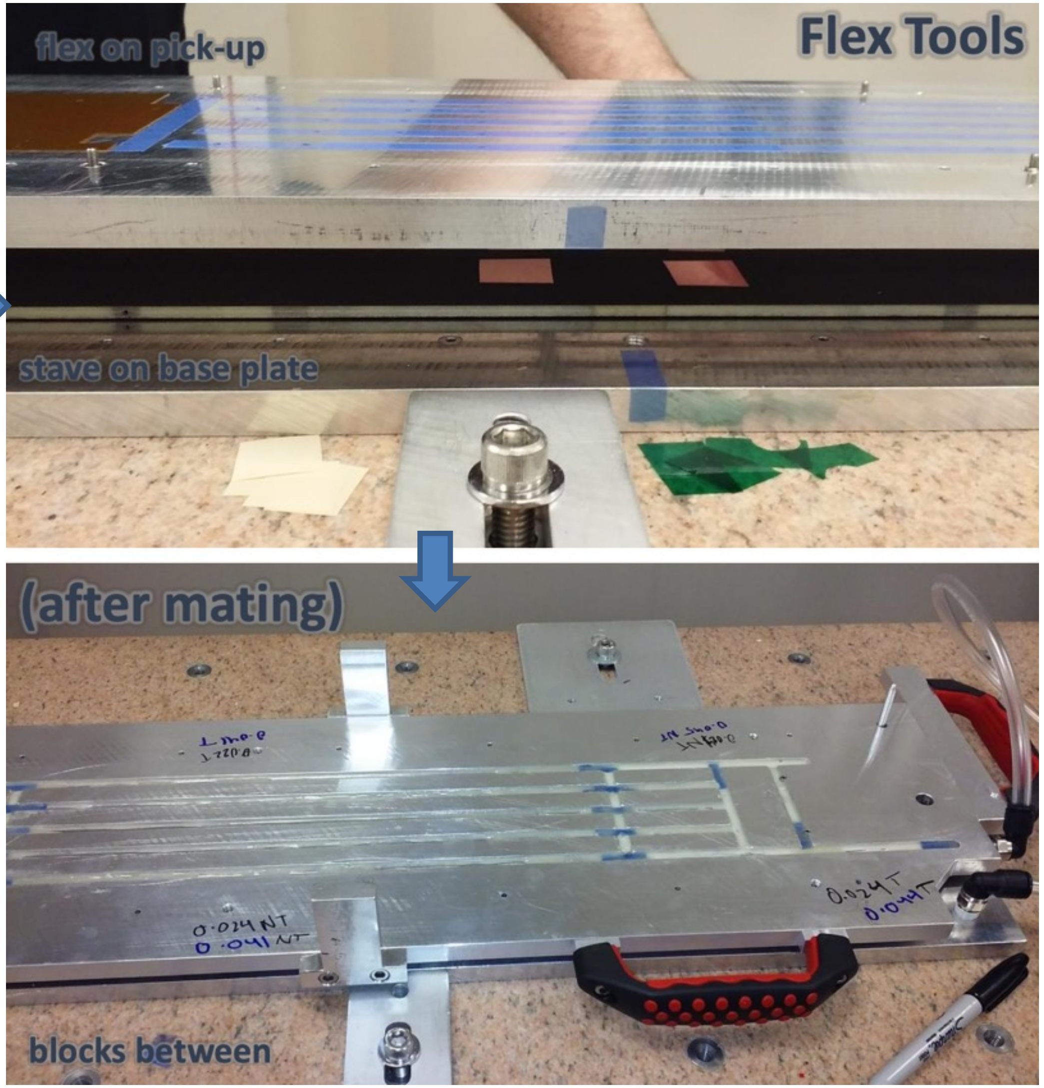


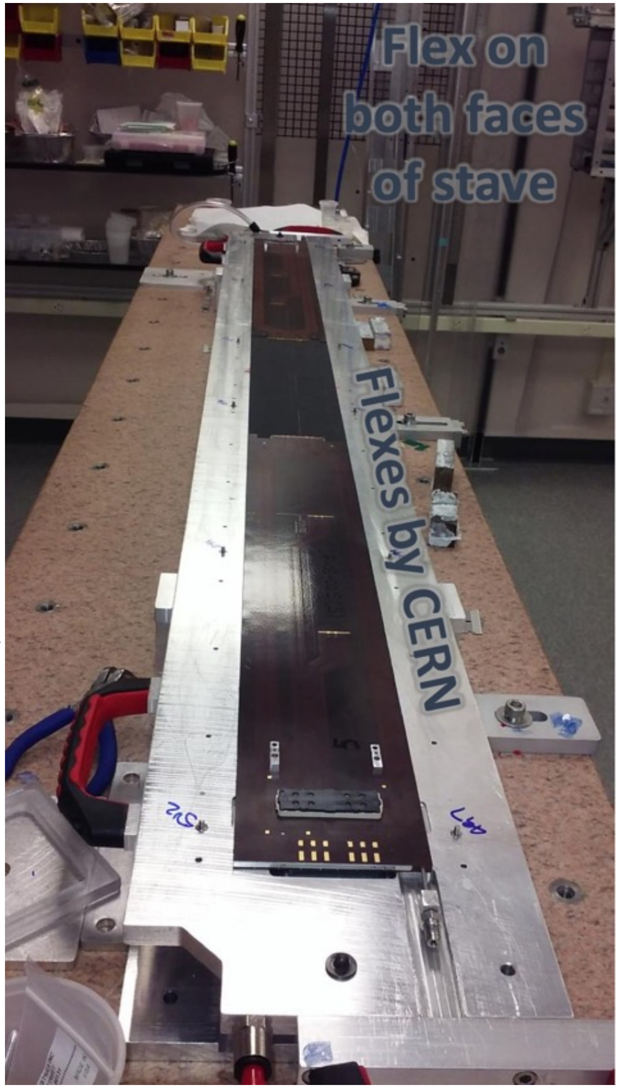




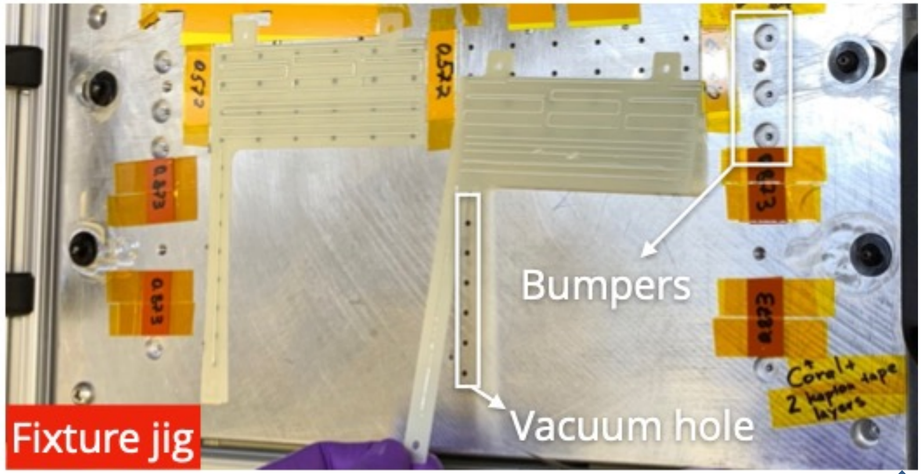
Flex attachment

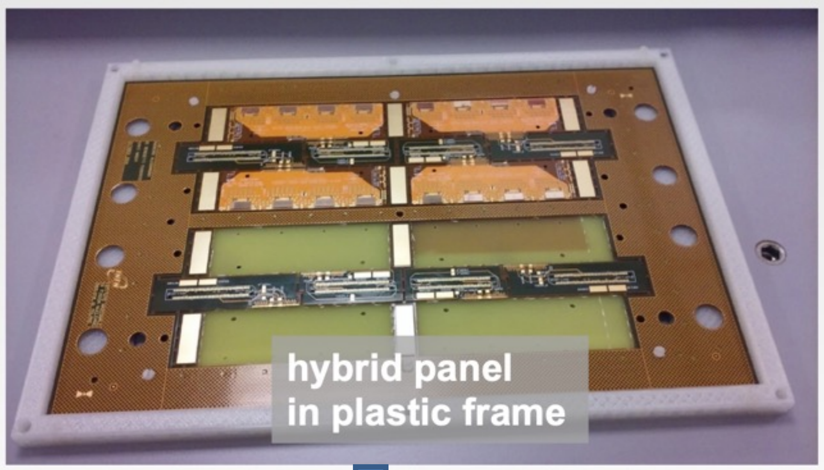


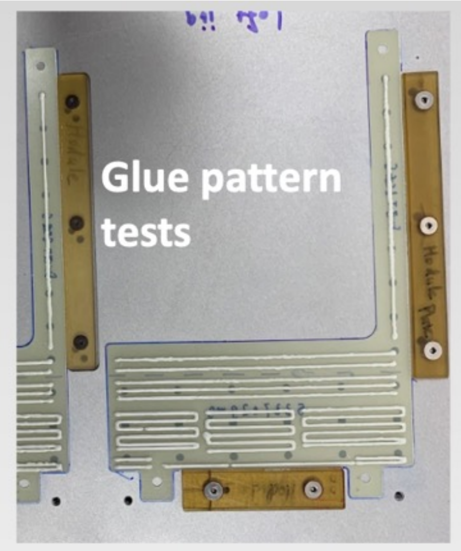


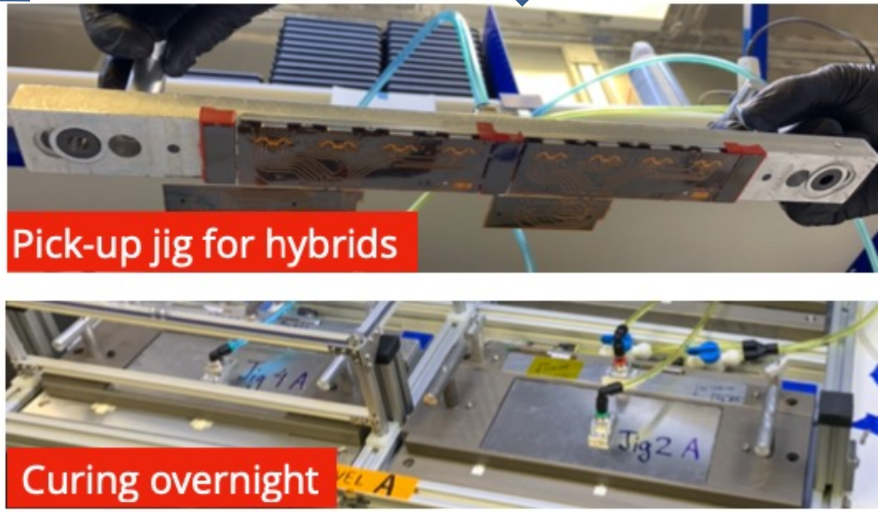


Module assembly

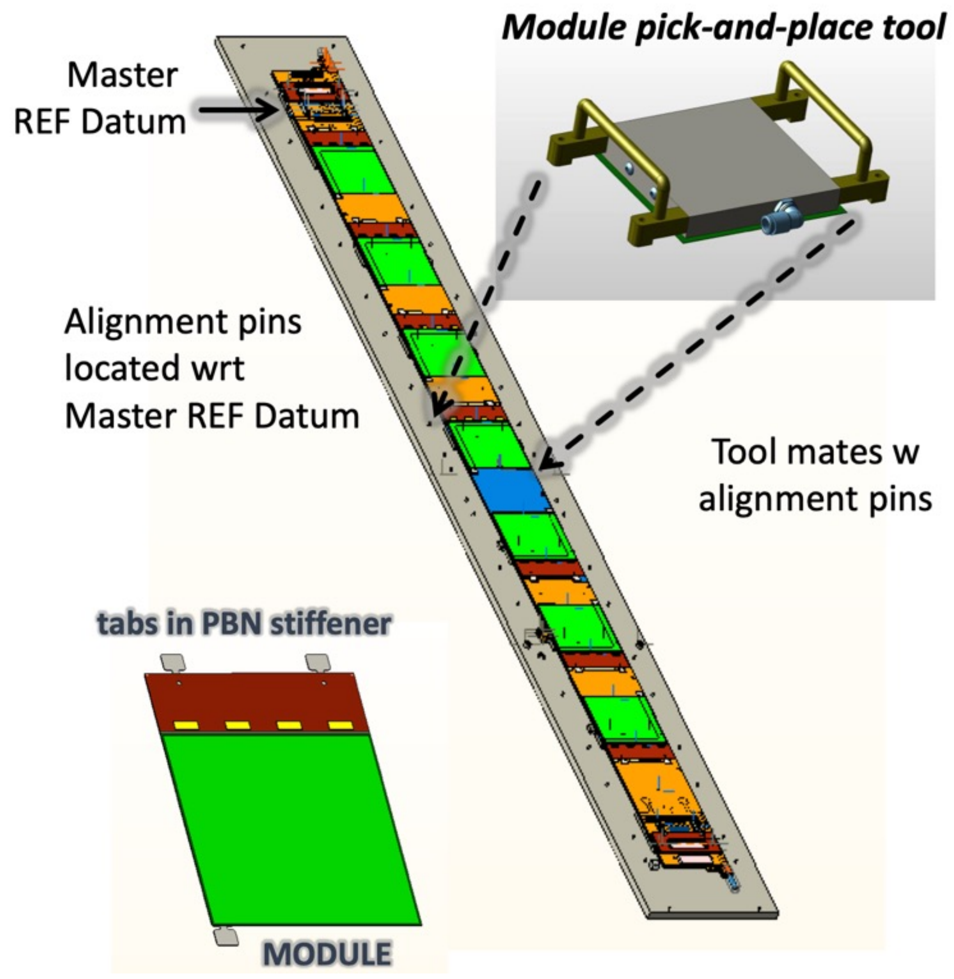


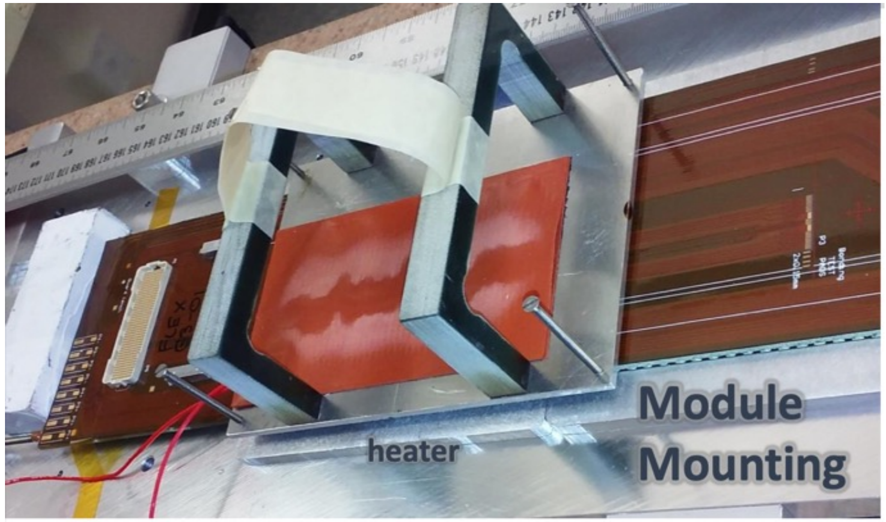


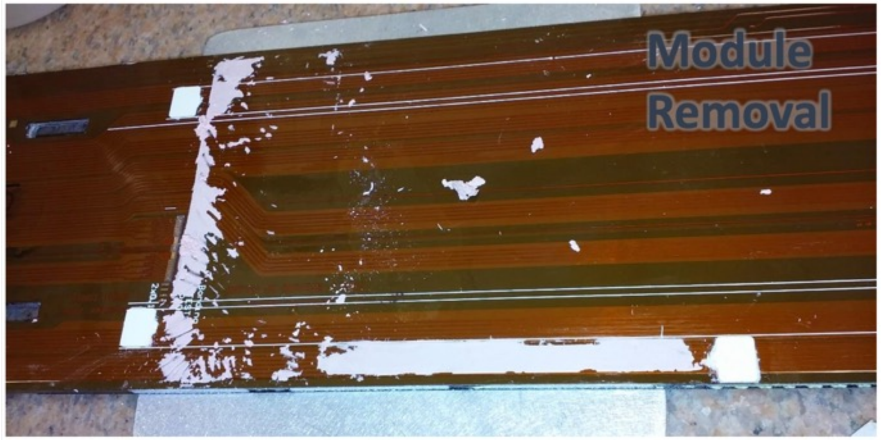


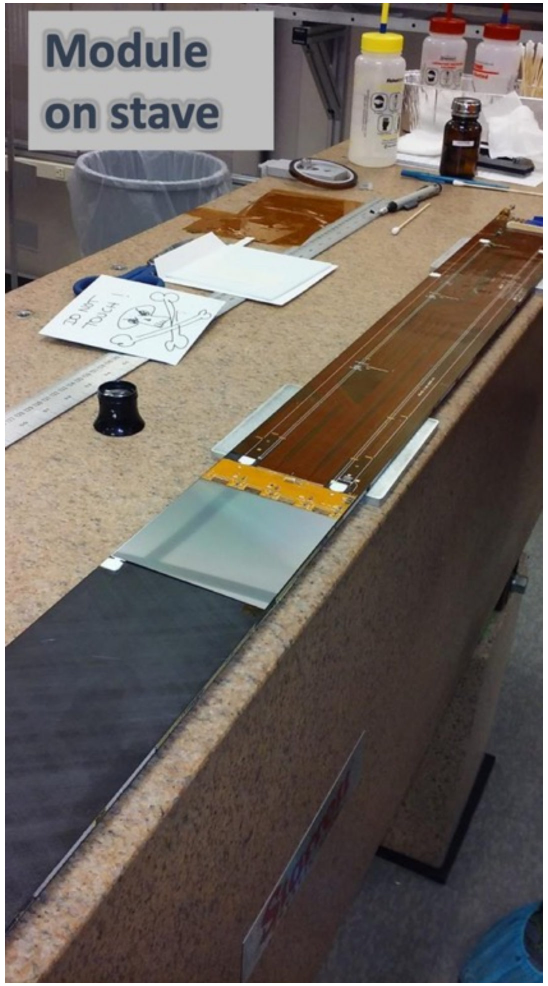


Module mounting





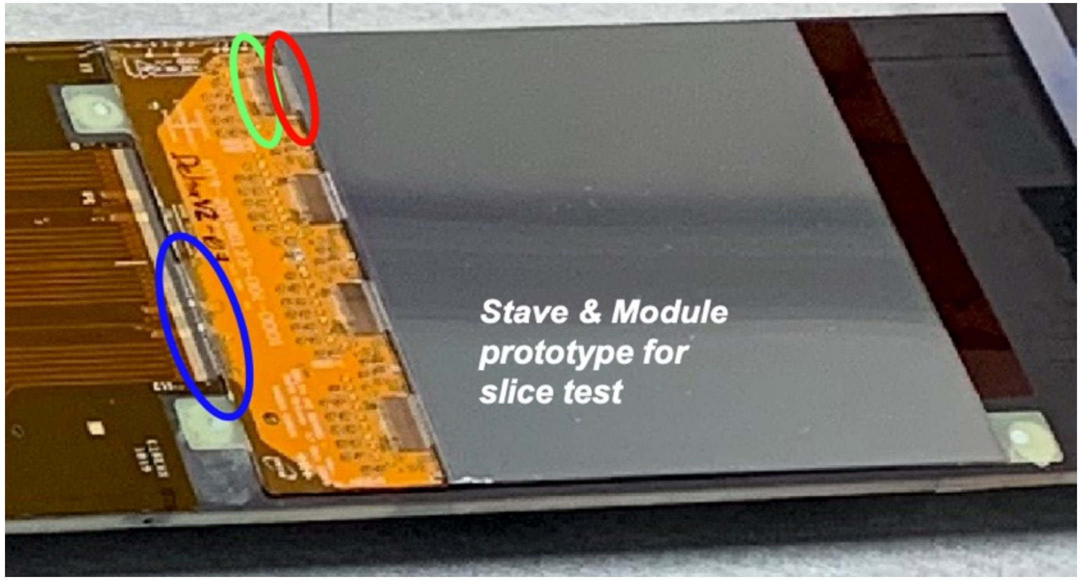




Wire bonding

3 wire bonding steps

- ASICs -> hybrid
  - 135 bonds per ASIC, 540(1080) per module, pads 60-120um wide
- Sensor -> ASICs
  - 512(1024) bonds, pads 60-65um wide
- Hybrid -> Flex Cable
  - ~80 bonds per module, pads 200um wide



~15K bonds per stave, >1M overall

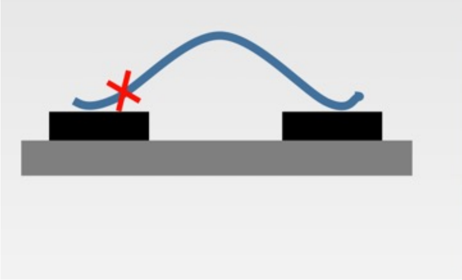
Quality requirements

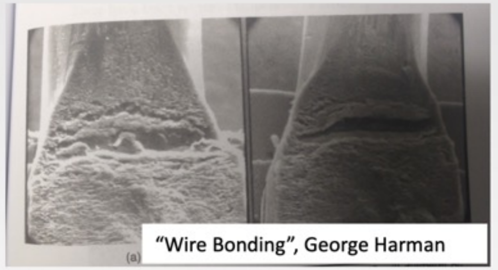
- Reliability: <<0.1% failures
- Bond strength: >5g (with mean at 8-10g)

Equipment

- F&K Delvotek G4 6400 + 25um al wire
- Doge 4000 pull tester for QA

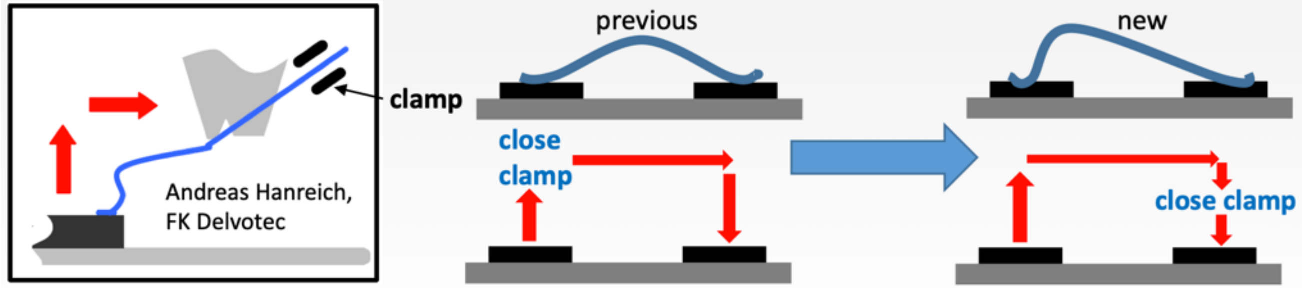
Improvements





Loop shape process adjustments

- Most of the bonds broke in the same place near the foot of the 1st bond
- Change clamping sequence

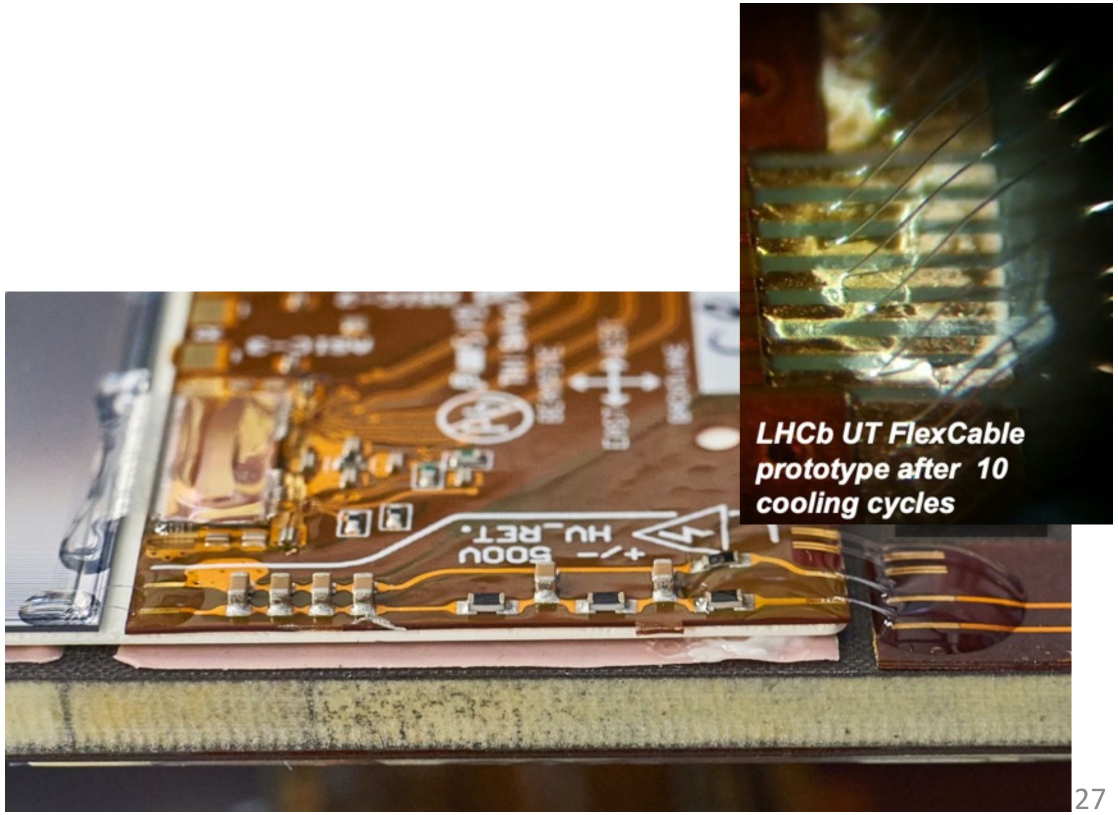


Observed corrosion after several cooling cycles

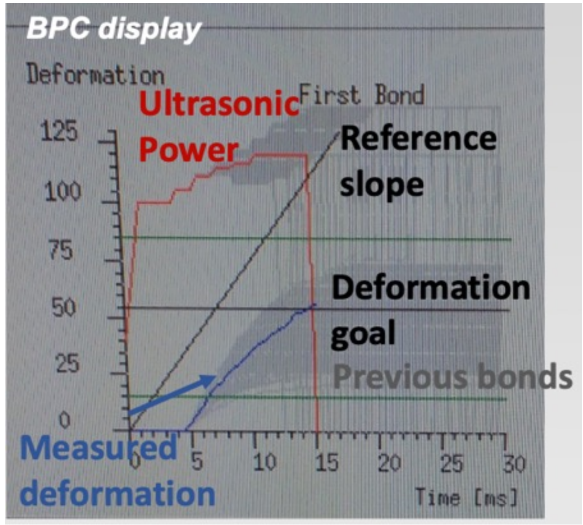
- White residue on bonds: Al reaction with water

Pot feet for all bonds

- No mechanical protection, only for corrosion

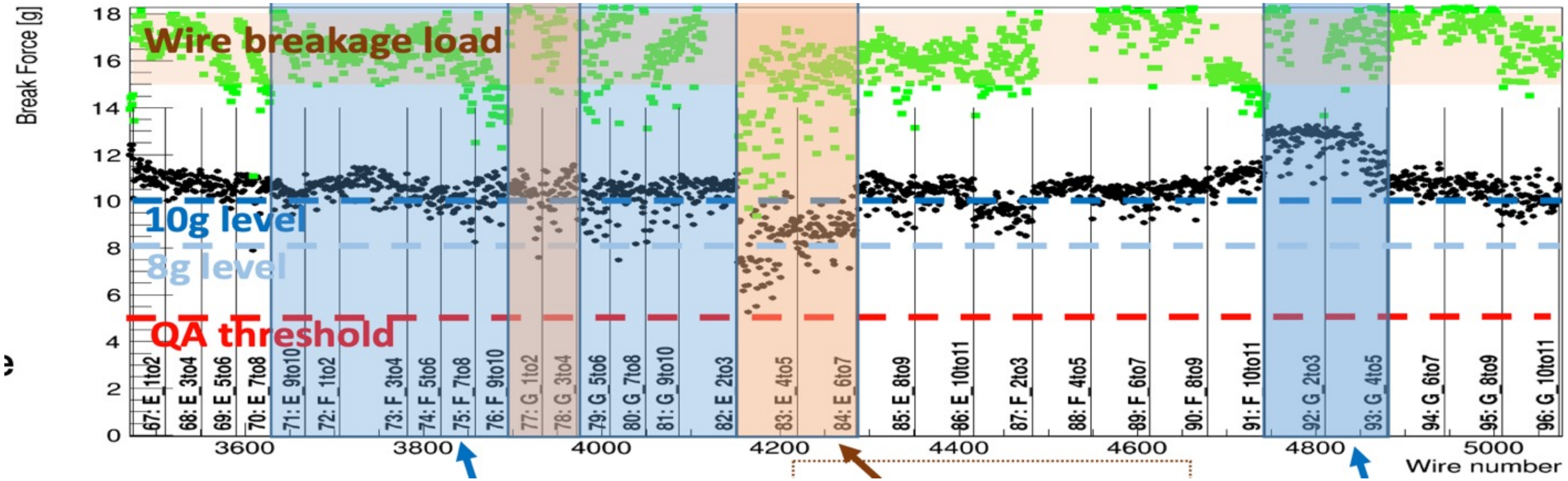


Wire bonding QA



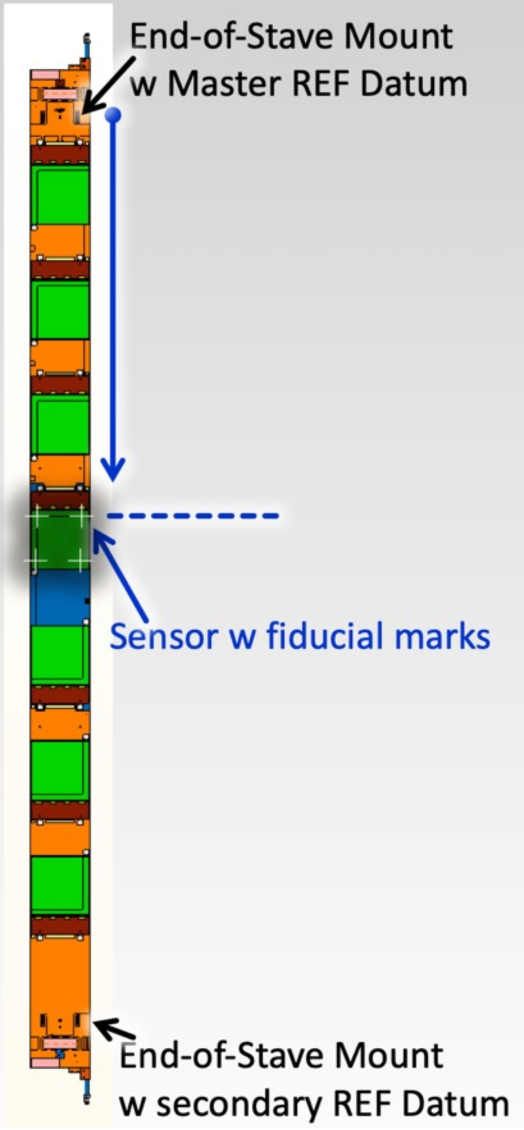
Adjusted BondProcessControl (BPC)
- Adjust ultrasonic power/stop bonding based on wire deformation measured online

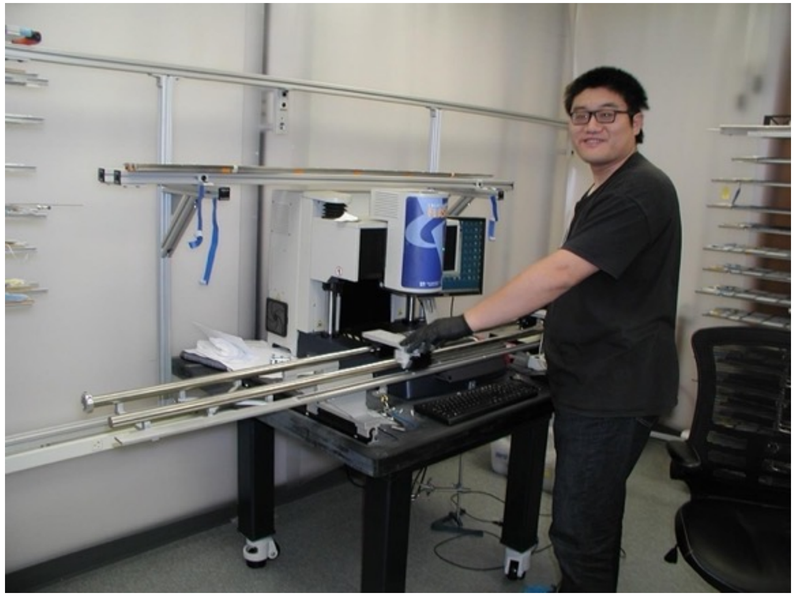
Parameters optimized based on thousands pull tests
- Contamination/vibration/degradation tests done



1/800 broke at less than 8g

Optical QA





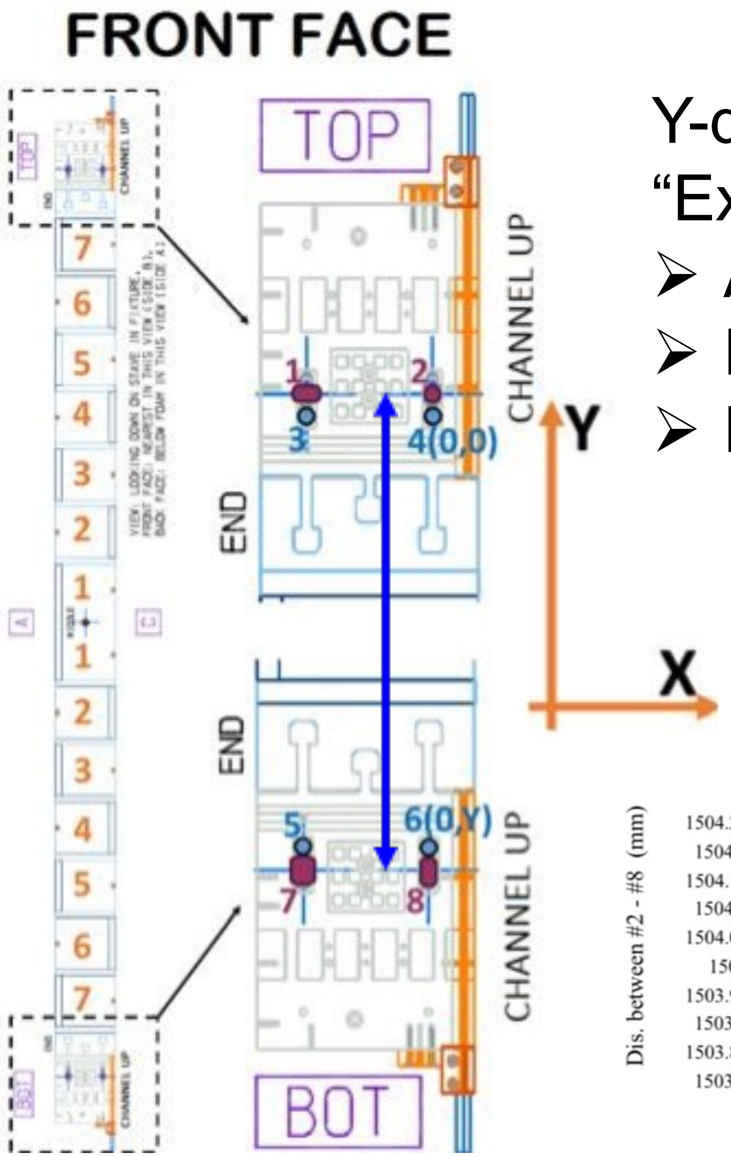
Sensor location wtr stave ref. datum
- Alignment marks $\sigma < 1\ \mu m$
- Feedback for stave construction
- Inputs for online tracking alignment

Optical QA also measure
- Size
- Flatness
- Tube direction …

QVI@ SmartScope™ Flash 200
- $\sigma \sim 1\ \mu m$

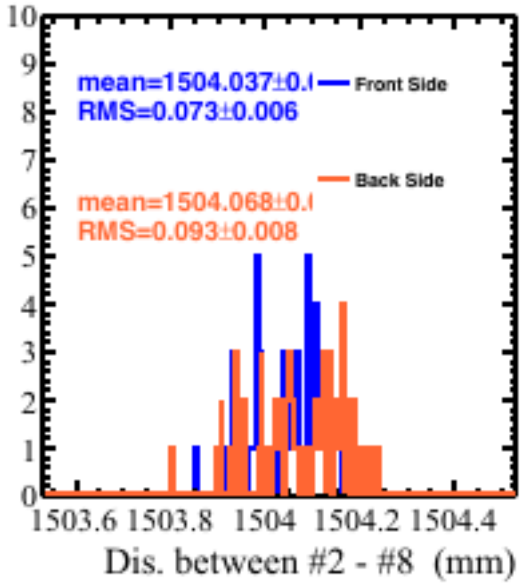
A rail system built for stave measurement
- XY travel from 20×20 cm $\Rightarrow 244 \times 20$ cm
- After calibration, the precision $\sim 10\ \mu m$

Length metric for constructed staves

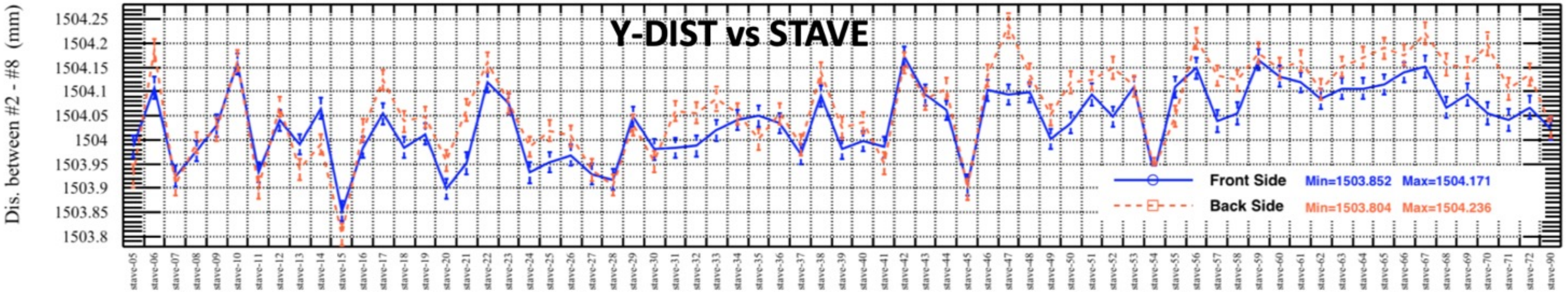


Y-distance from top to bottom mounting holes
"Excess" metric gives comparison to target

- Average under 50 um (accuracy)
- RMS within 100 um (precision)
- Range within +/- 200 um

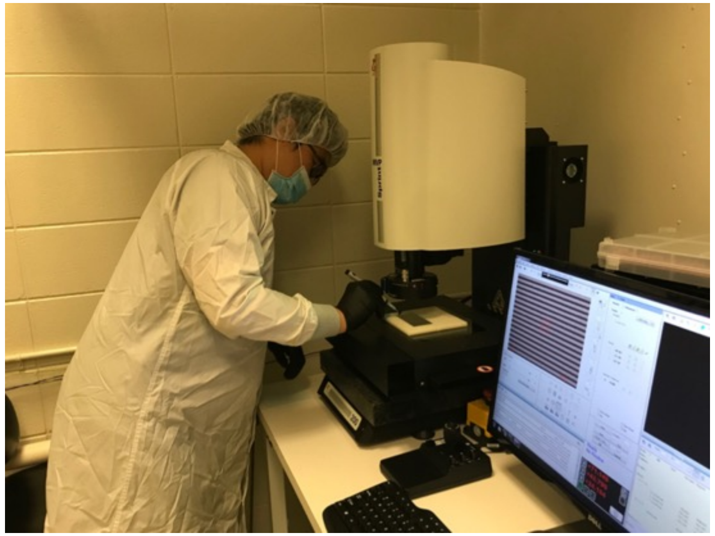


HOLE #	ELEMENT		Y [mm]	RMS	MIN	MAX	"EXCESS" [mm]	MIN	MAX
#2 - #8	MNT-T1	FRONT	1504.037	0.073	1503.854	1504.171	0.007	-0.176	0.141
	to MNT-B1	BACK	1504.068	0.093	1503.804	1504.236	0.038	-0.226	0.206
		CAD	1504.030	–					

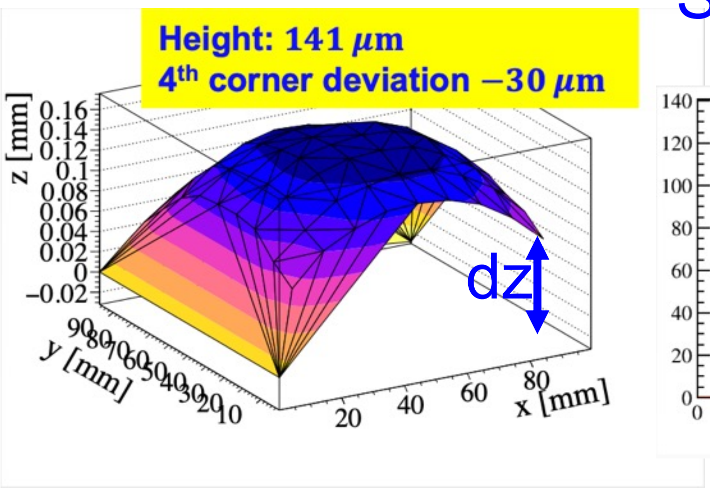


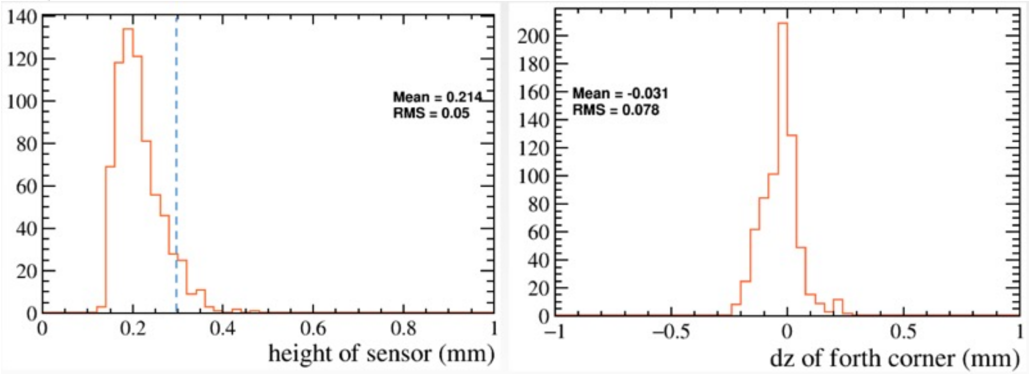
Optical QA for silicon sensors

Q/A before construction
- >1K sensors from Hamamatsu
- Metrology: bow measurement
- Visual inspection: defects from cutting along the edges + scratches/defects
- Electrical tests: IV/CV scans



Sensors with too large bow shape will be marked as "problem"



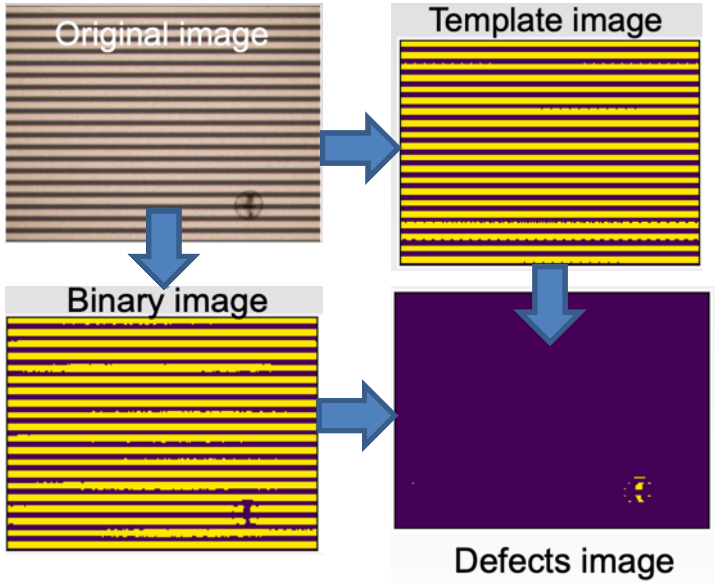


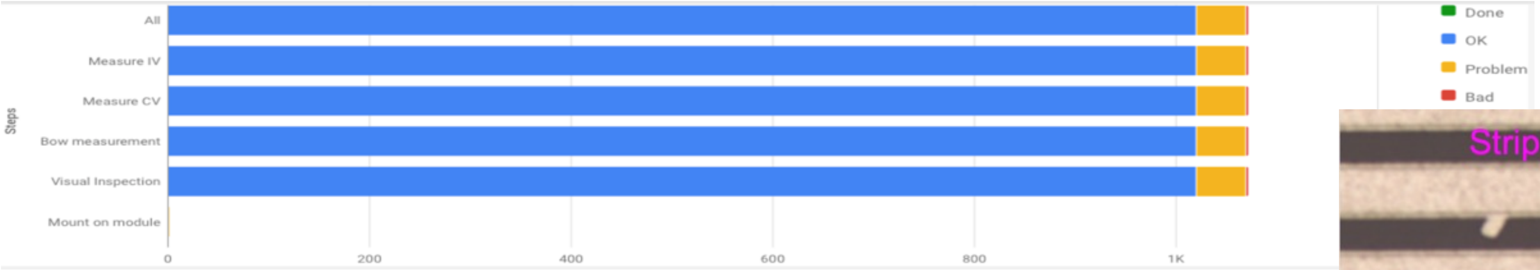
- Average height: 214 um
- Average dz: -31 um

Visual inspection

1. >1K sensors checked by eyes with microscope
2. SmartScope shoots ~700 micro-pictures on sensor surface for 1 sensor, totally 7M pictures
   - ➢ Tons of man power + high rate for mistakes

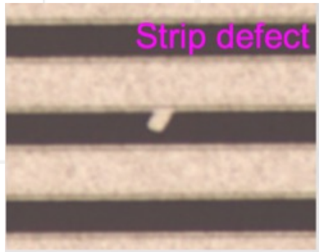
A graph script for searching ”bad” picture automatically
- ➢ 0.3s for each micro-picture

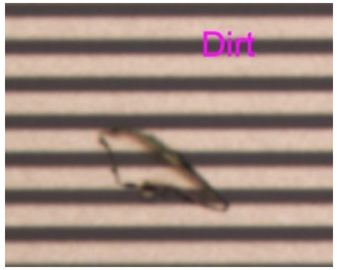


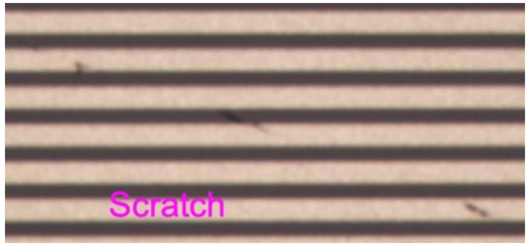


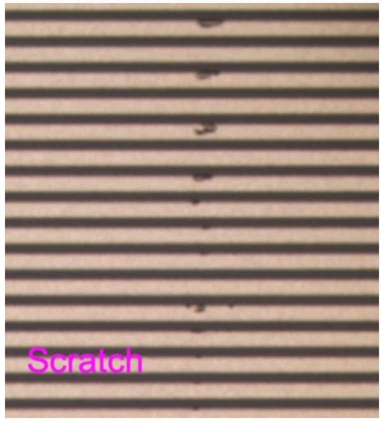
Optical QA for all sensors
- ➢ 49 marked as “problem”: defects or bad metrology ⇒ spares
- ➢ 3 marked as “bad”: scratch/broken

“bad” sensors





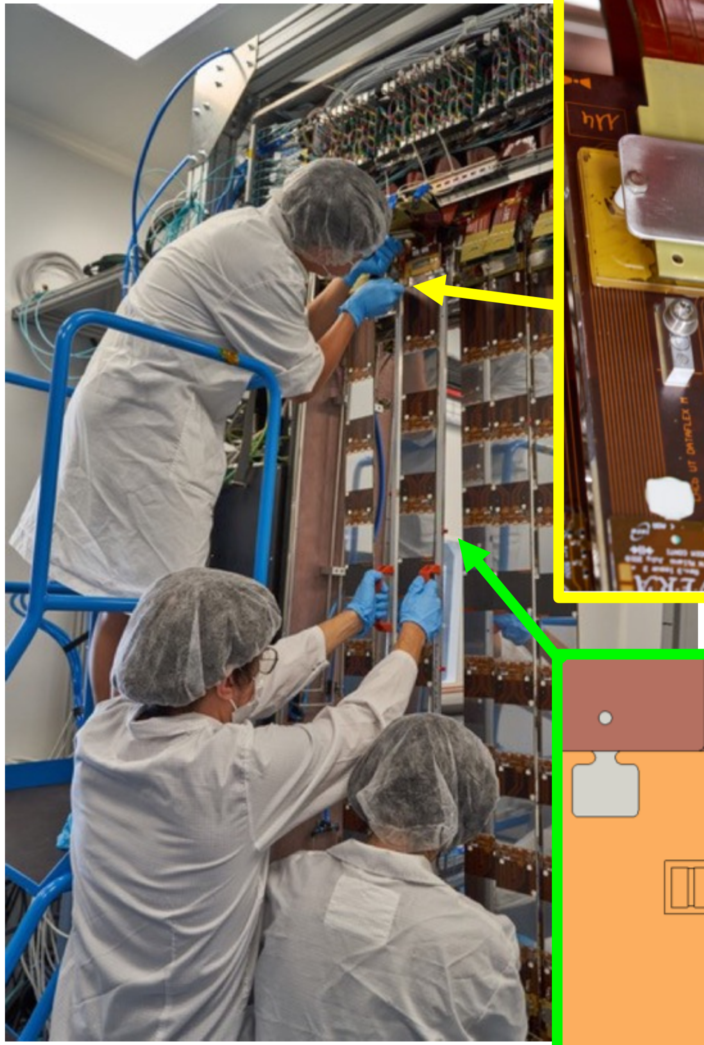


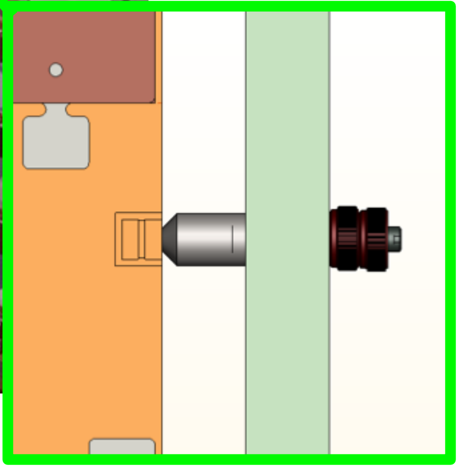


Installation @ CERN

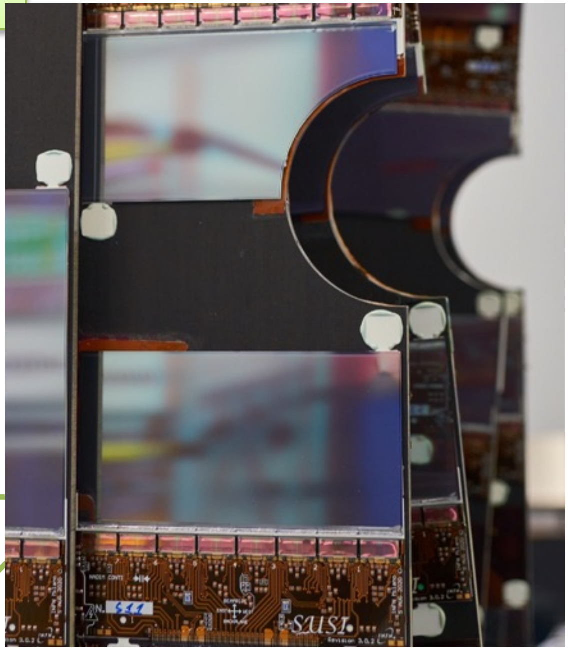
I am hungry for staves

Stave installation





1. Stave installation on supporter with long narrow-size screws ⇒ allow stave move ~mm
2. HV pins connected + validation of the mapping
3. Back face pigtails connected
4. Stave adjusted to final position and fixed
5. Front face pigtails + CO_2 tubes connected
6. Electronic tests

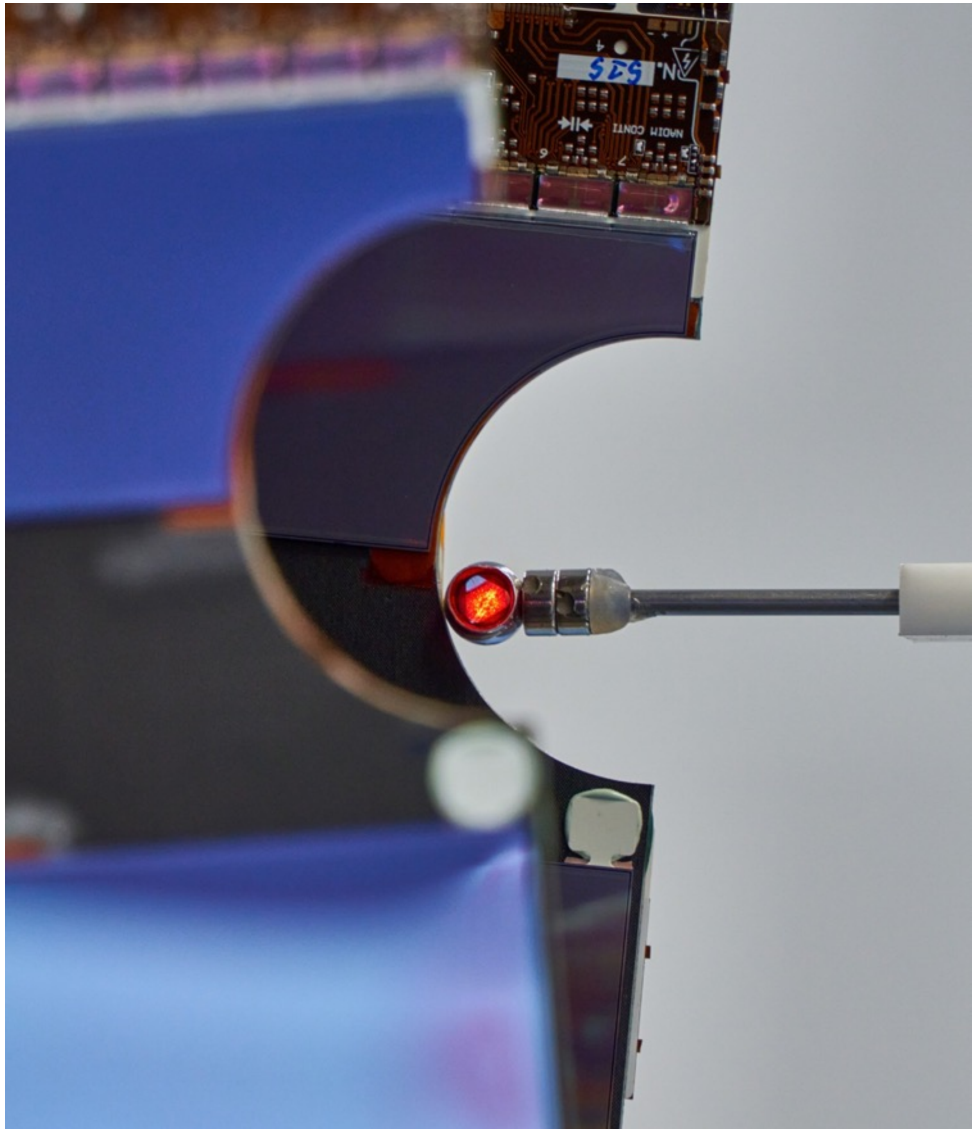


Survey

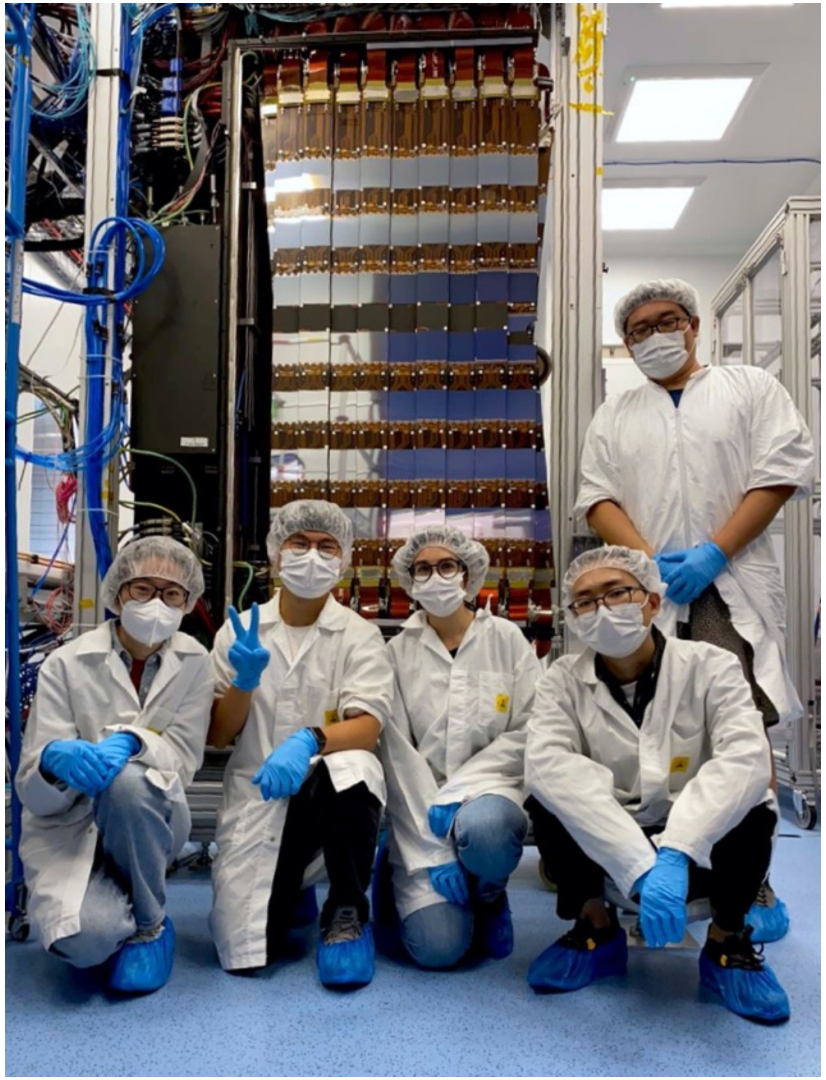
Stave positions validated with photogrammetry measurements. Stave installed on average within 0.5 mm in X, 0.2 mm in Y. Angle less than a milliradian from nominal

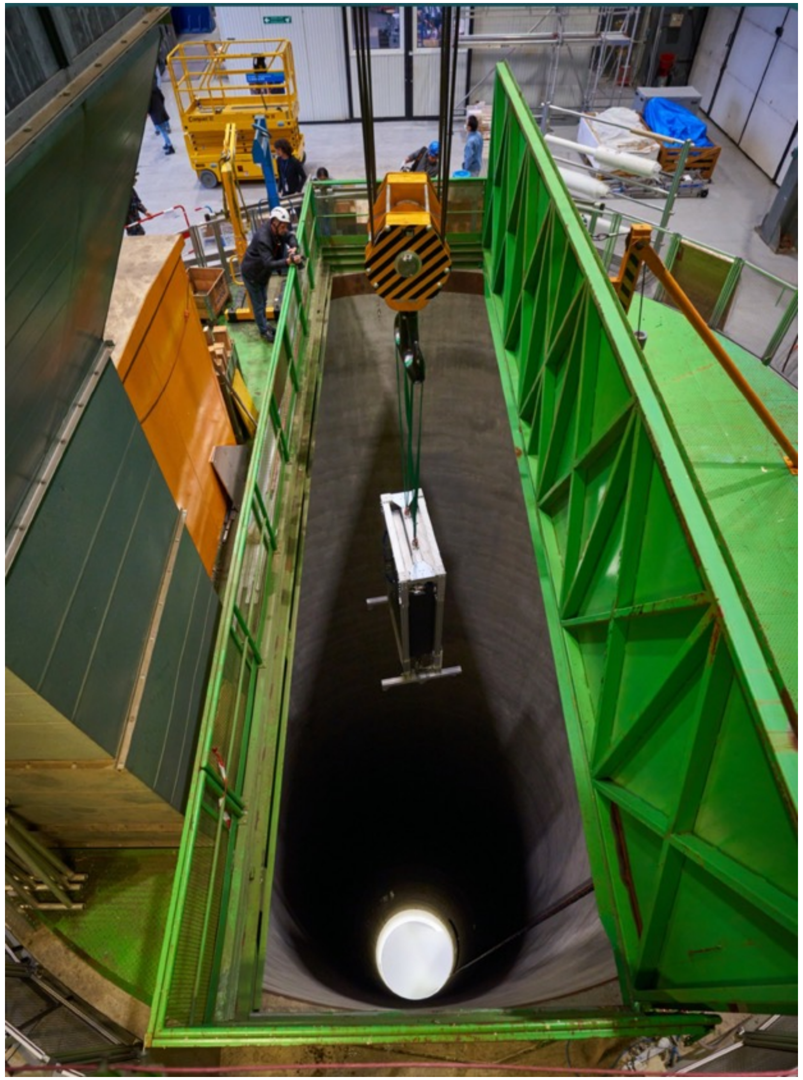
High importance the positions of the innermost staves with the beam pipe cut out. Enough clearance to ensure that due to contraction during operation there will no interference

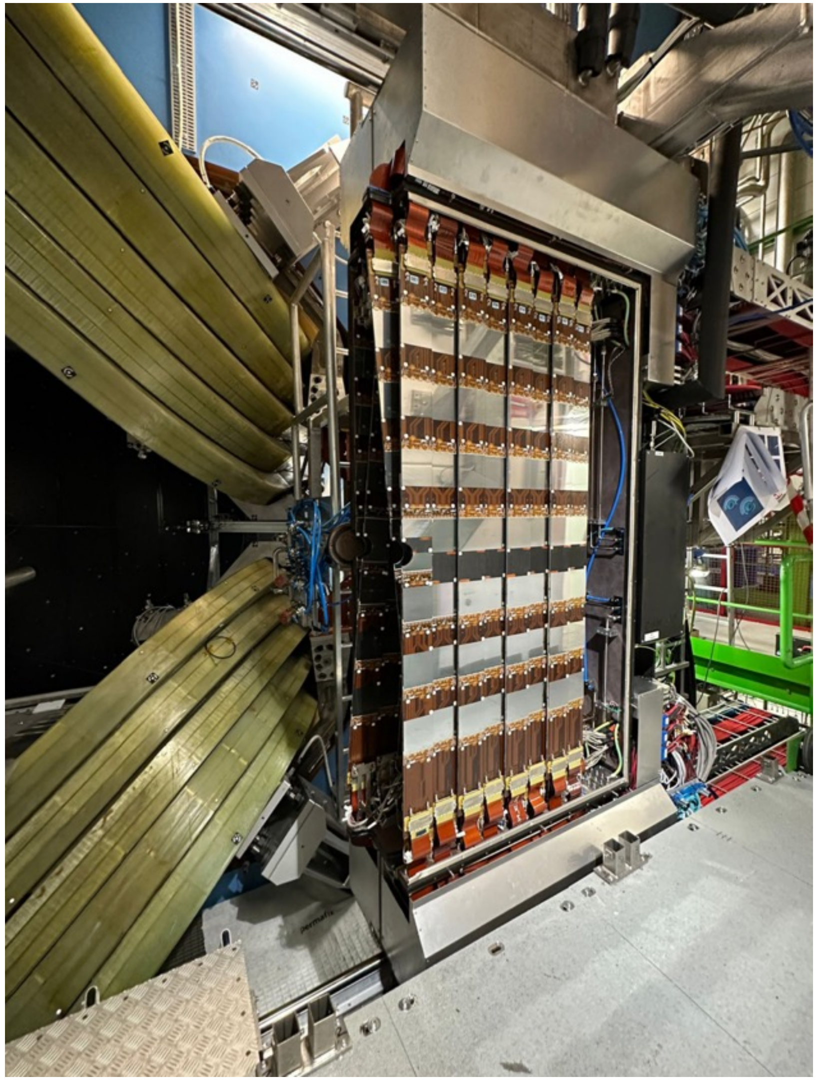
The position of the one of the staves was adjusted in order to comply with the requirements and be safe with the beam pipe and with the box enclosure



Lowered UT







UT story almost done, but we have another story for new UT or U2UT

Upgrade II UT (U2UT)

LHCb China group will lead this upgrade

Channel occupancy [%]

0.42	0.45	0.47	0.49	0.52	0.54	0.57	0.60	0.60
0.46	0.49	0.52	0.56	0.59	0.63	0.68	0.74	0.77
0.53	0.58	0.62	0.68	0.73	0.83	0.89	1.00	1.06
0.64	0.70	0.77	0.86	0.96	1.10	1.26	1.48	1.63
0.78	0.88	0.97	1.13	1.27	1.54	1.81	2.34	2.72
0.96	1.10	1.23	1.45	1.68	2.05	2.63	2.84	3.87
1.28	1.45	1.54	1.81	2.04	2.57	3.42	4.48	3.95 5.13

Beam pipe

Current UT optimized for $\mathcal{L}_{\text{Run 3\&4}}$

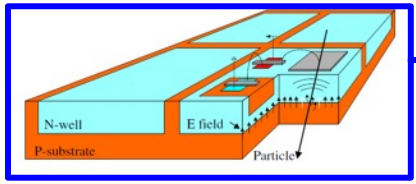
Upgrade II luminosity $1.5\text{x}10^{34}$ $cm^{-2}s^{-1}$ (x7.5 $\mathcal{L}_{\text{Run 3\&4}}$)

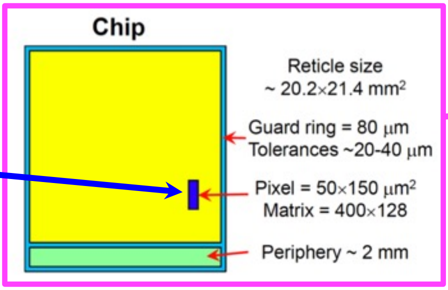
- The occupancy (max ~10%) will compromise the performance
- Radiation does too high for current sensor

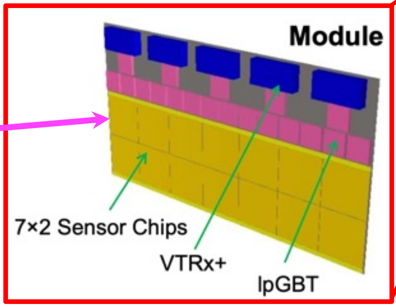
U2UT:

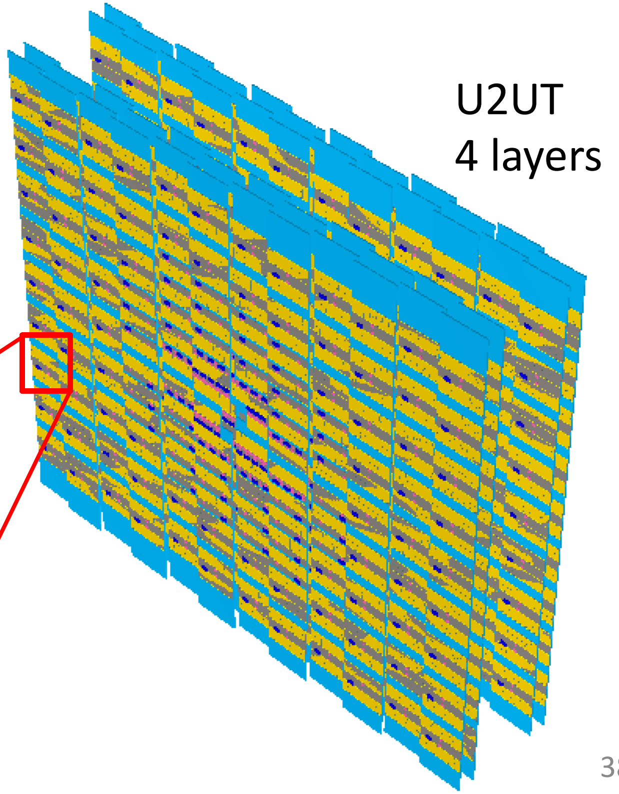
- CMOS MAPS technique applied
  Very promising and cost effective for large area pixel detectors.

Monolithic Active Pixel Sensor (MAPS)



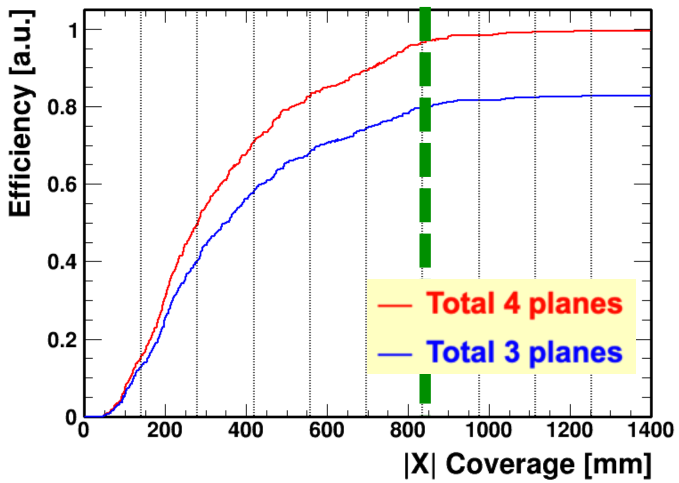




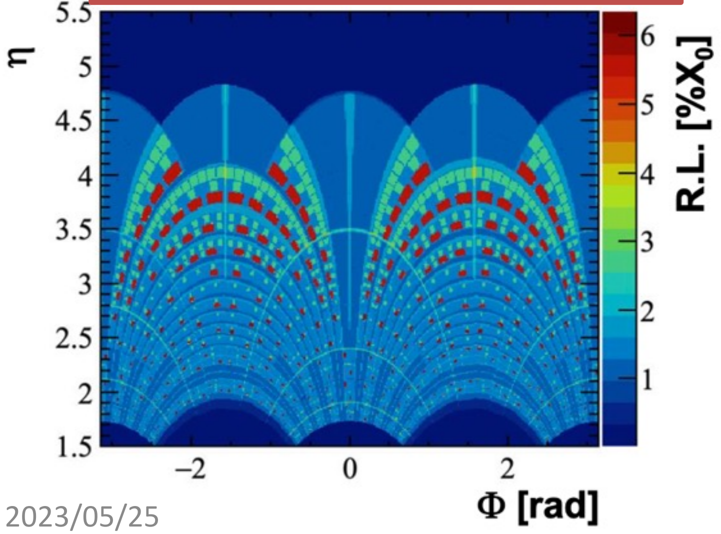


U2UT R&D status

Track efficiency vs X coverage



R.L. as functions of Φ and η

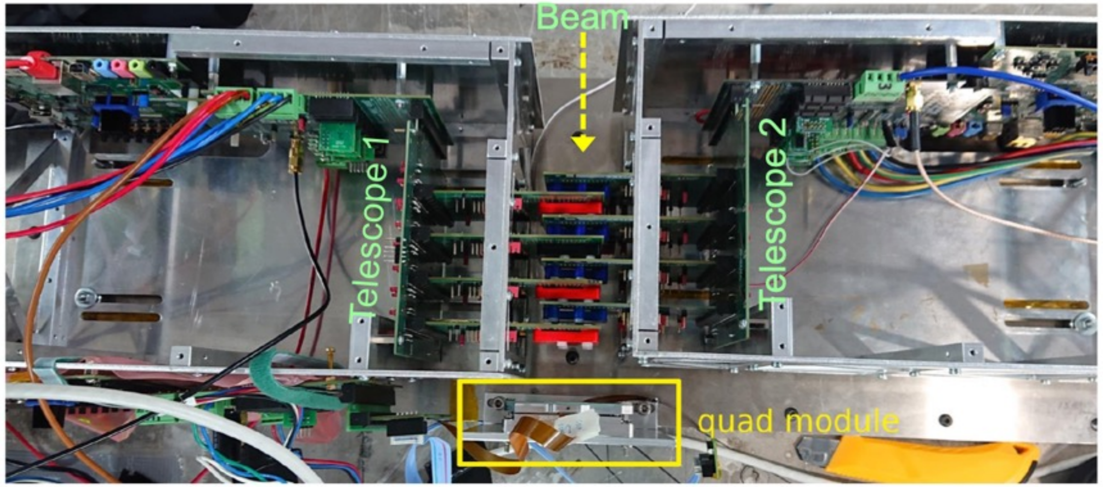


U2UT software ⇦ Lead by LHCb China group

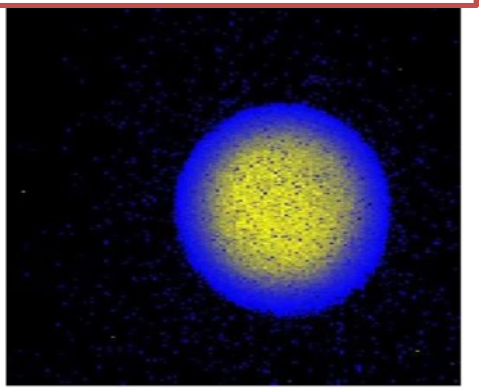
- Preliminary studies on
  - Track efficiency for $B^- \to D^0 K^-, D^0 \to K_s \pi^+ \pi^-, K_s \to \pi^+ \pi^-$ Optimizing U2UT coverage
  - Detector simulation mostly done and RL calculated

U2UT chips

- Beam test @ DESY in April 2022
- Tested in cosmic ray and various radioactive sources



Hitmap with Fe55 source



Summary

LHCb plans upgrades

- Upgrade1, Upgrade1b and Upgrade2

UT: key for tracking system

- Tracks reconstructed faster, more efficiently …
- Installation done, commission/online software nearly done

U2UT: replace current UT in the future

- FTDR is ready and now we are in R&D phase