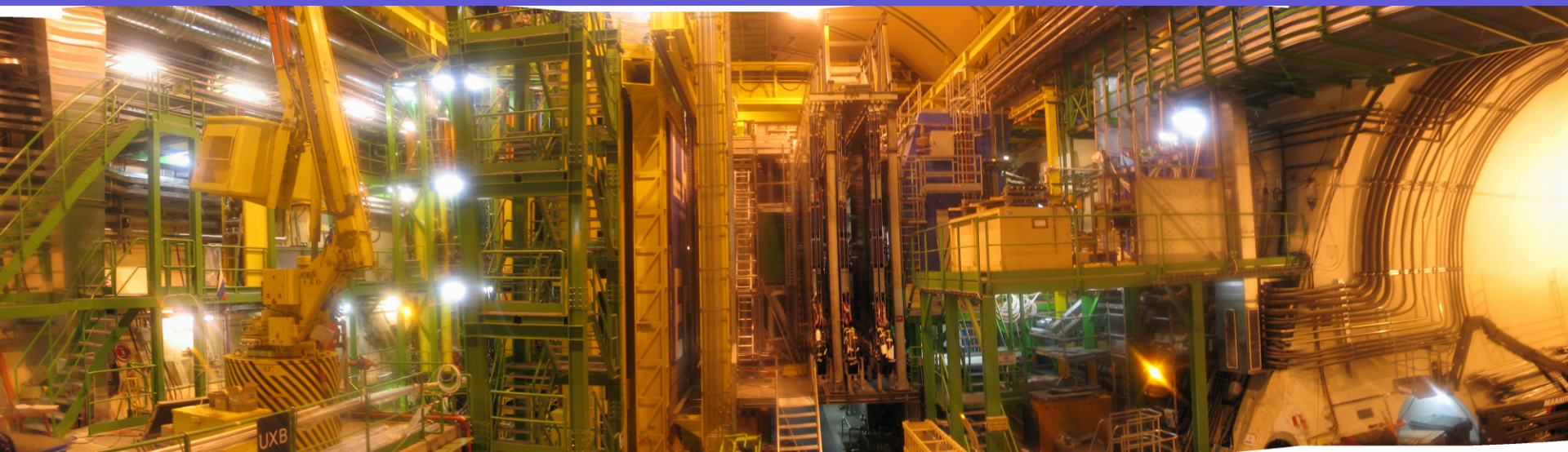
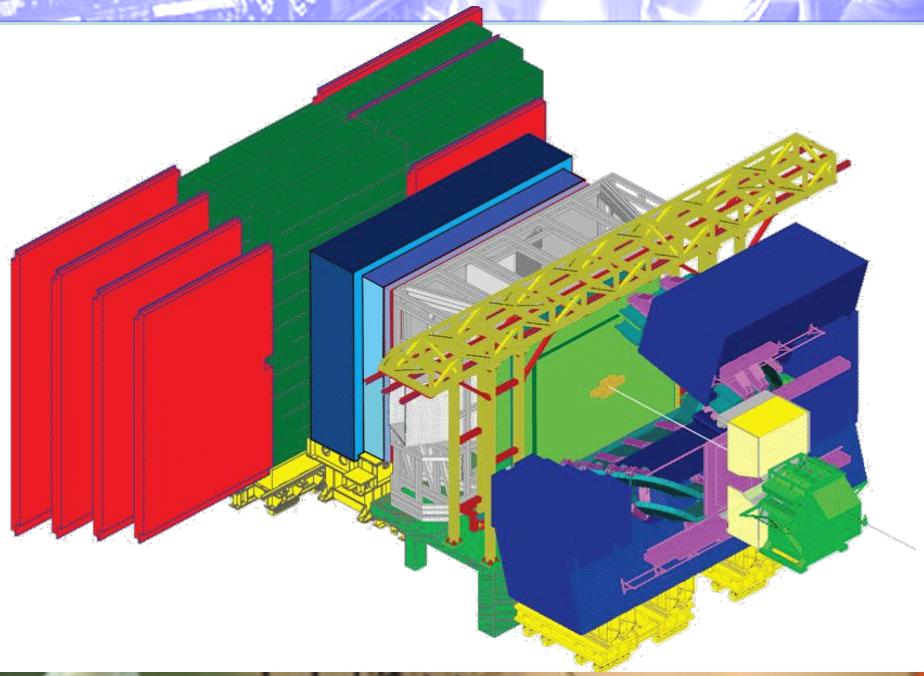
LHCb Vertex Detector

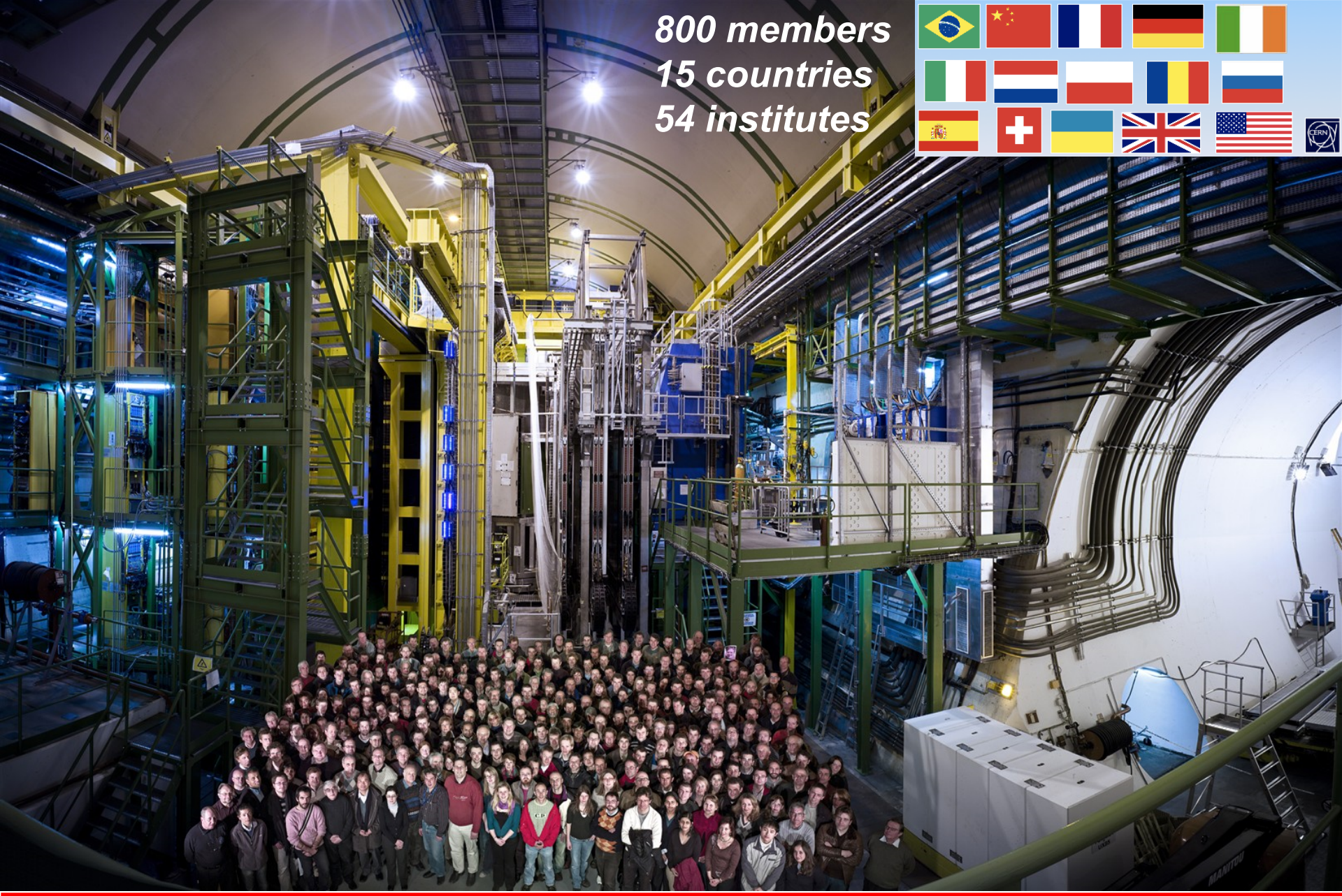
T. Bowcock



Overview

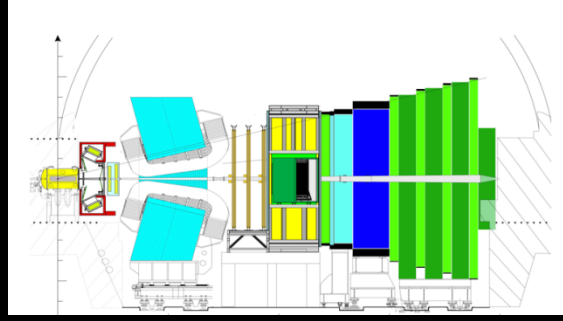


- LHCb & VELO
- Assembly & Construction
- Operation & Performance
- Issues
- Summary

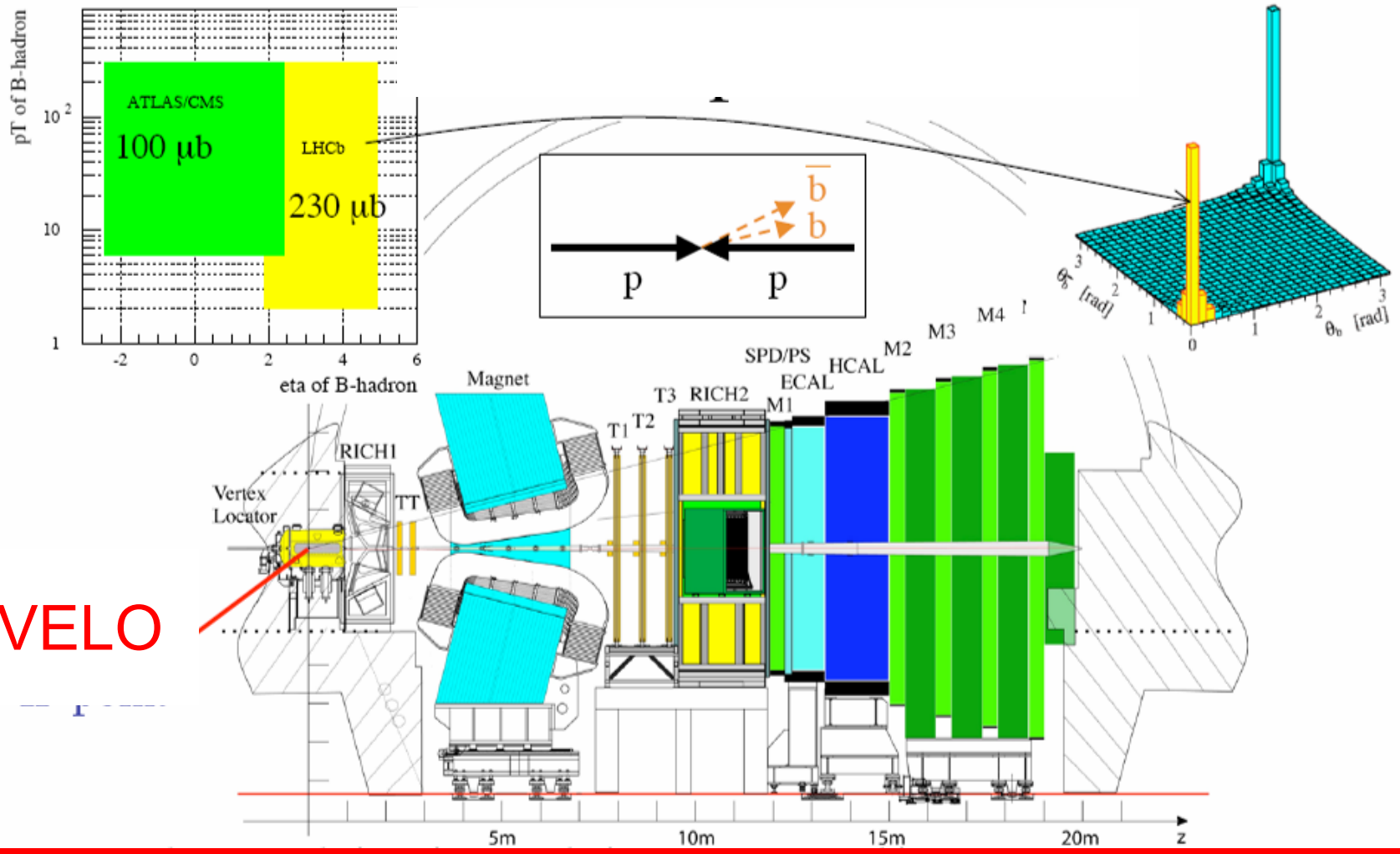


UNIVERSITY OF LIVERPOOL

The Detector



LHCb: Spectrometer

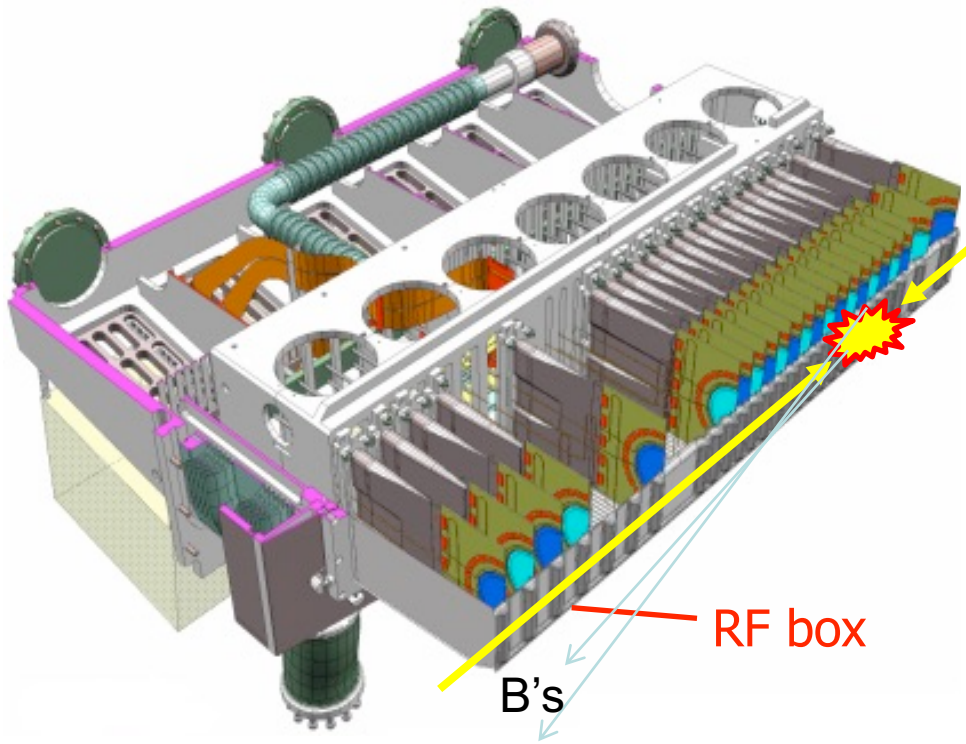


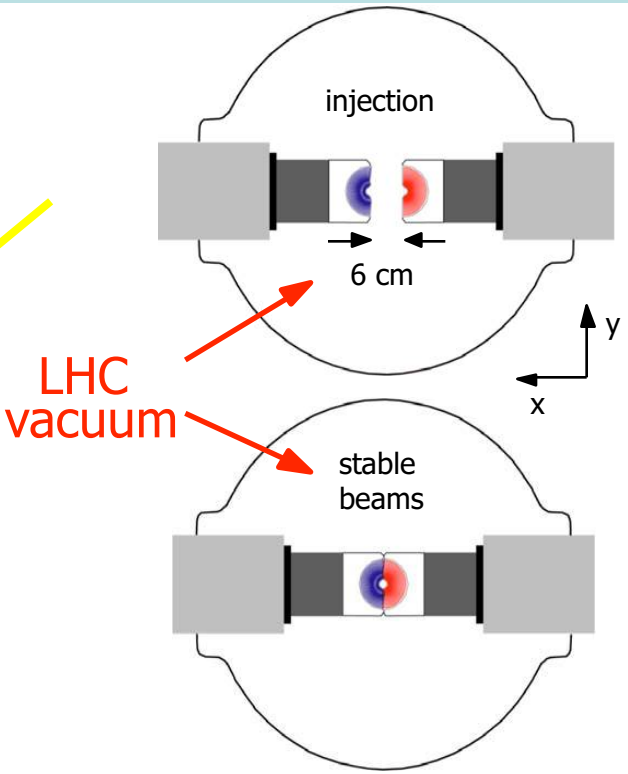
VELO

LHCb: VELO Requirements

- Good vertexing
  - Primary vertex <10microns
  - IP parameter ~40μm (40fs time resolution)
    - close to LHC beam (vacuum)
  - high radiation levels $<10^{15}$p/cm^2
  - Close to Beam = moving detectors
- Tracking
- Low mass ~10% X_0

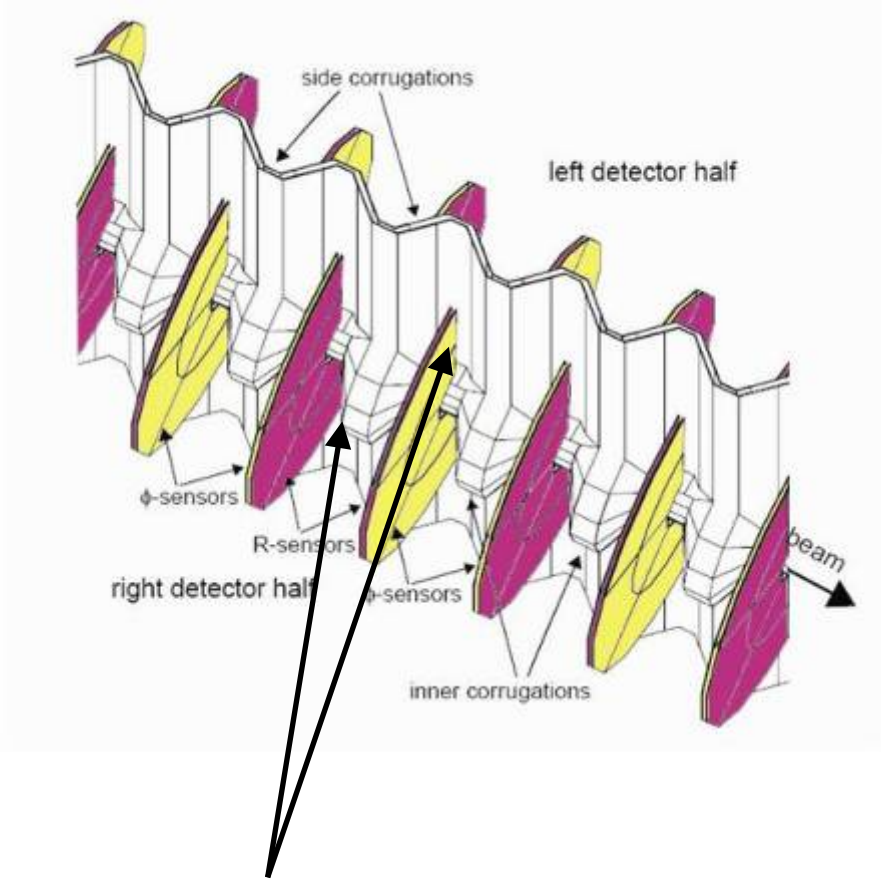
VELO: Schematic





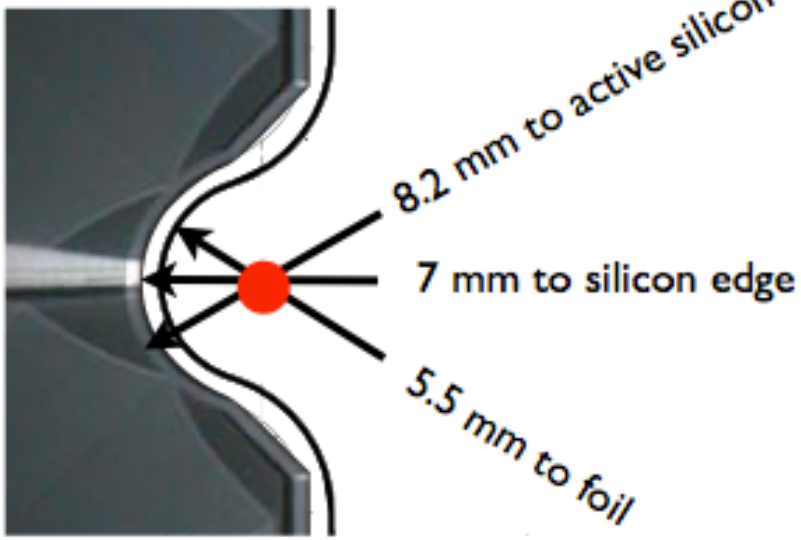
- 2 retractable detector halves
- 21 stations per half with an R and ϕ sensor

VELO: Tolerances



Approx 1mm clearance

Zoom of silicon and foil



VELO: Foils

VELO: Complete half

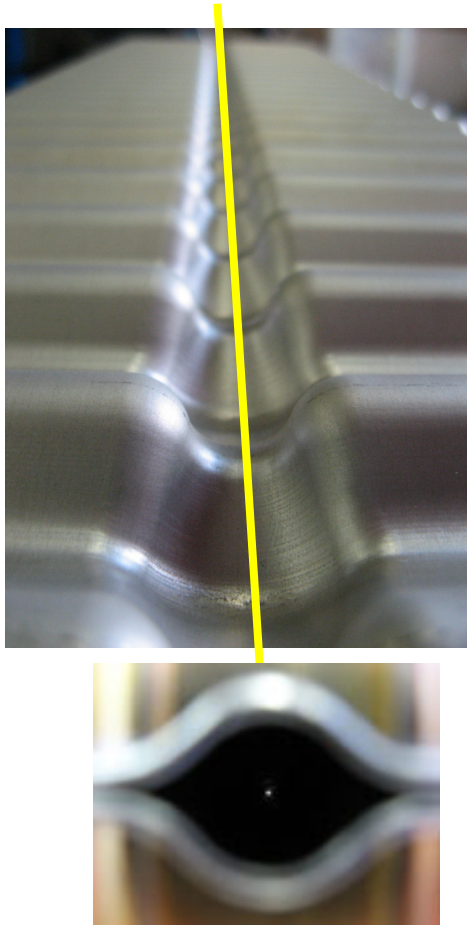
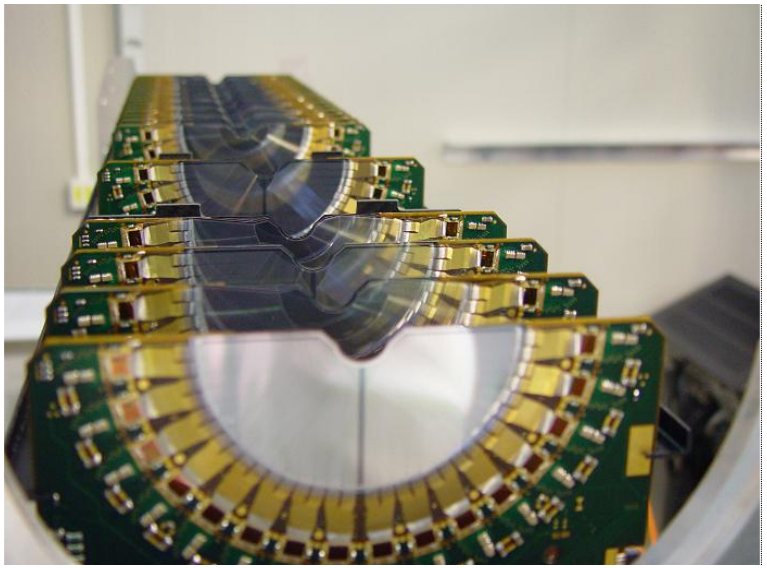
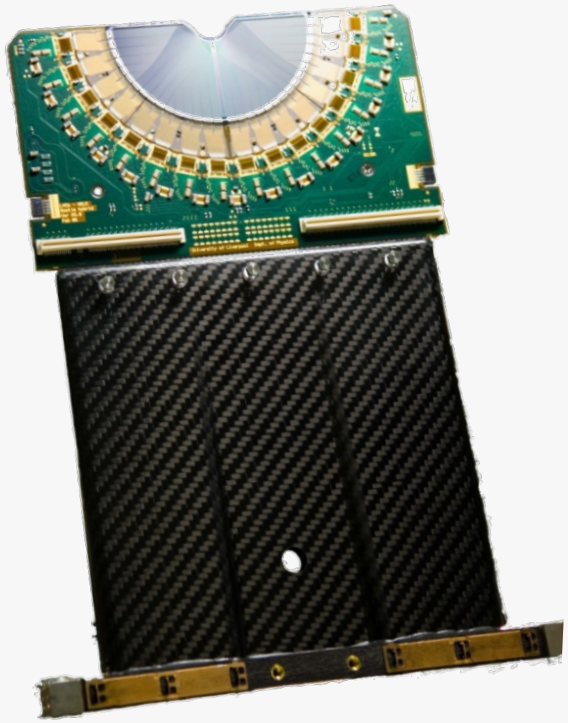
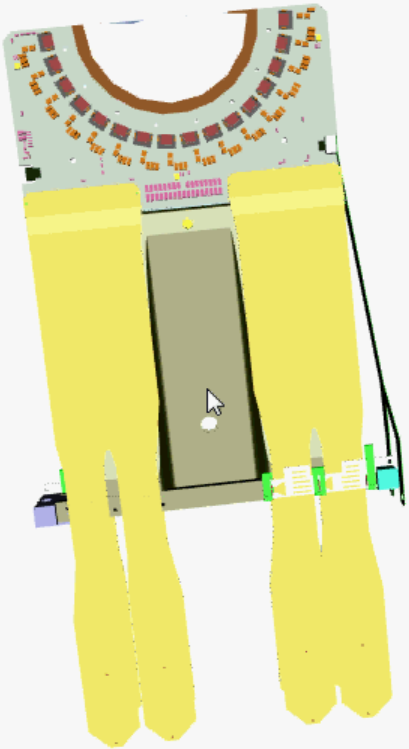


Photo along beam pipe



VELO: Module





Attempt O CTE construction

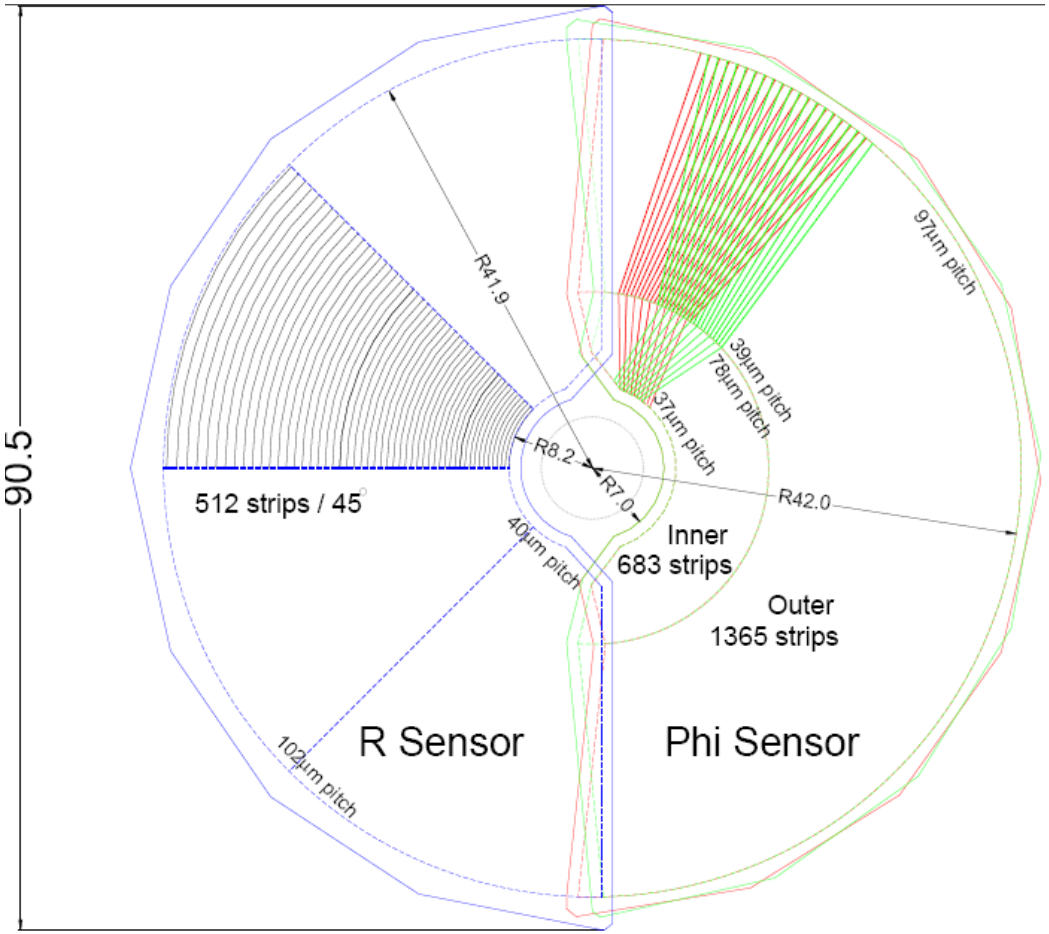
VELO: Electronics

- Analogue output from ASICS on hybrids
  - 40MHz: up to 1MHz trigger rate
  - Repeater cards outside tank
- Digitization 60m away
- FPGAs handle processing of signals and zero suppression
  - 10^6 parameters need uploading
  - 7bit arithmetic
    - Integer pedestals and CM subtractions
  - Possibility of non-zero suppressed data to be sent to storage

SENSORS

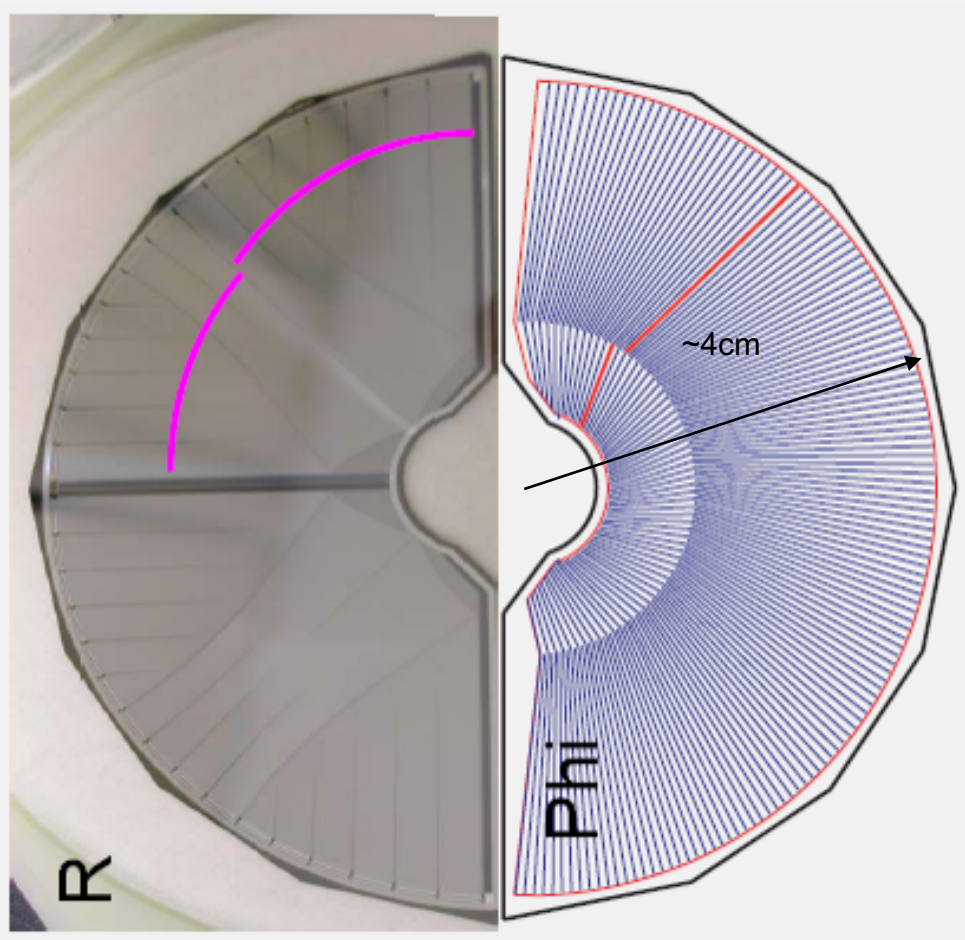
VELO: Sensors

- Double Metal for routing
- Closest Strip 8.2mm
- ~10 ° /20° Stereo
- Micron Semiconductor (UK)



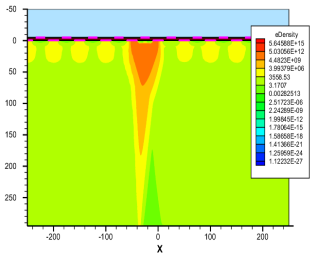
VELO: Sensors

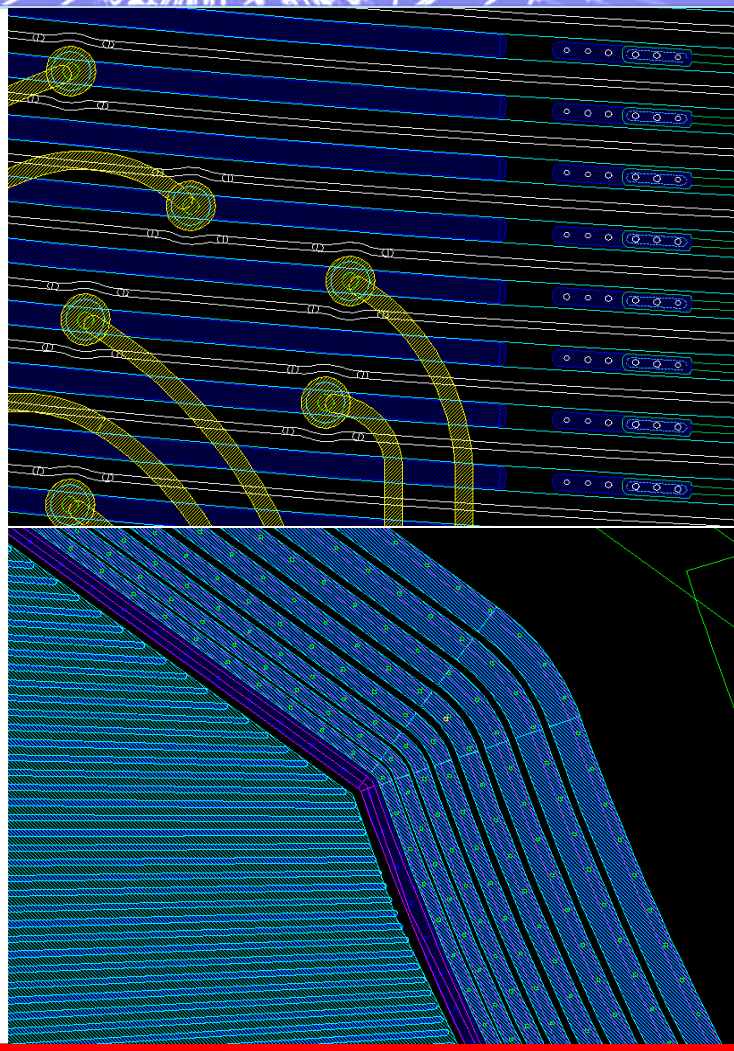
- highly segmented
- n^+n
  - One n^+p module
  - *Replacement n^+p*
  - p-spray isolation
- 2048 strips/sensor
- ~40 micron inner pitch



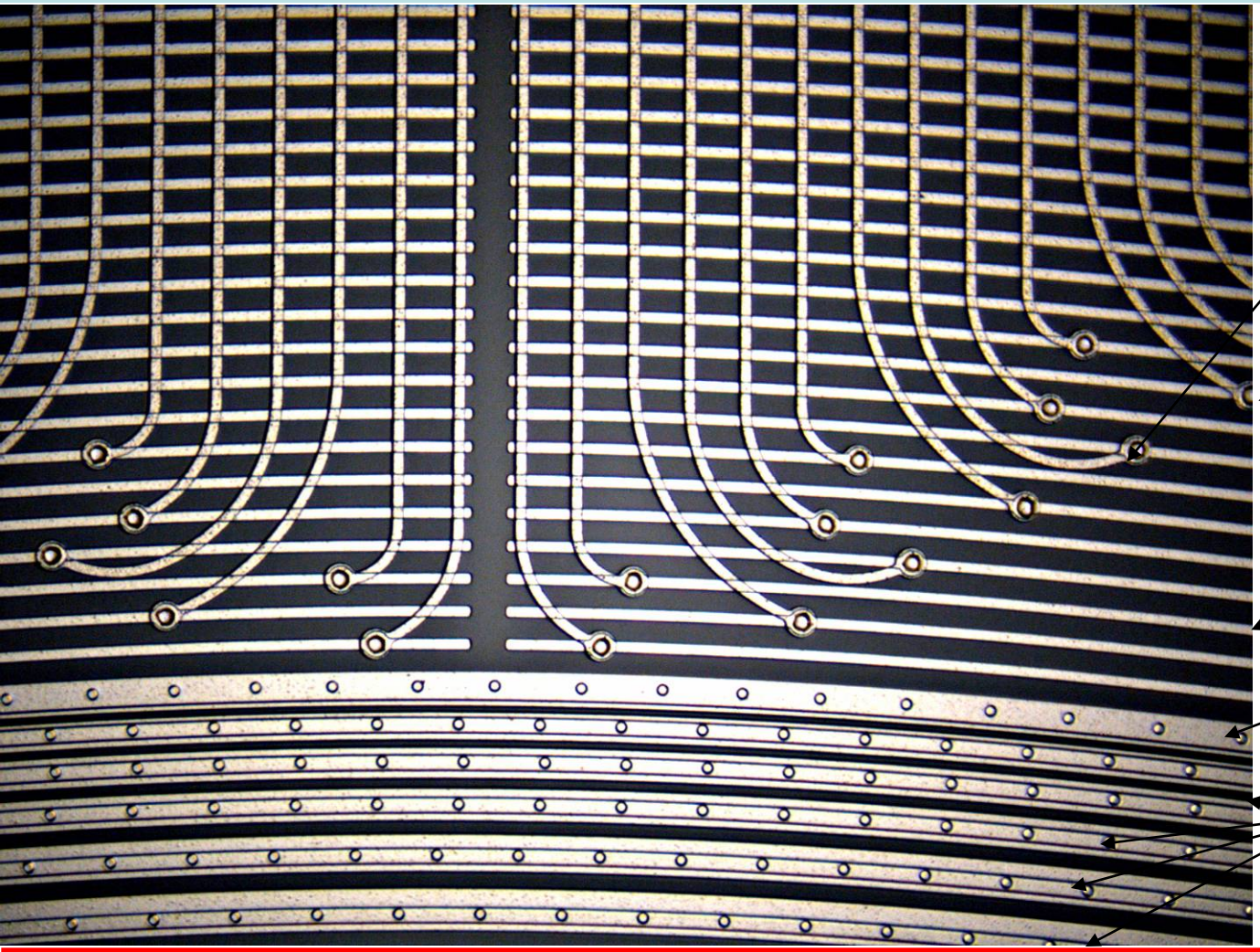
VELO: Sensors Design

- Simulated
  - Radiation damage
  - Expected resolution
  - Cross talk
  - Systematic cluster shifts
- Expect
  - Resolution ~5μm

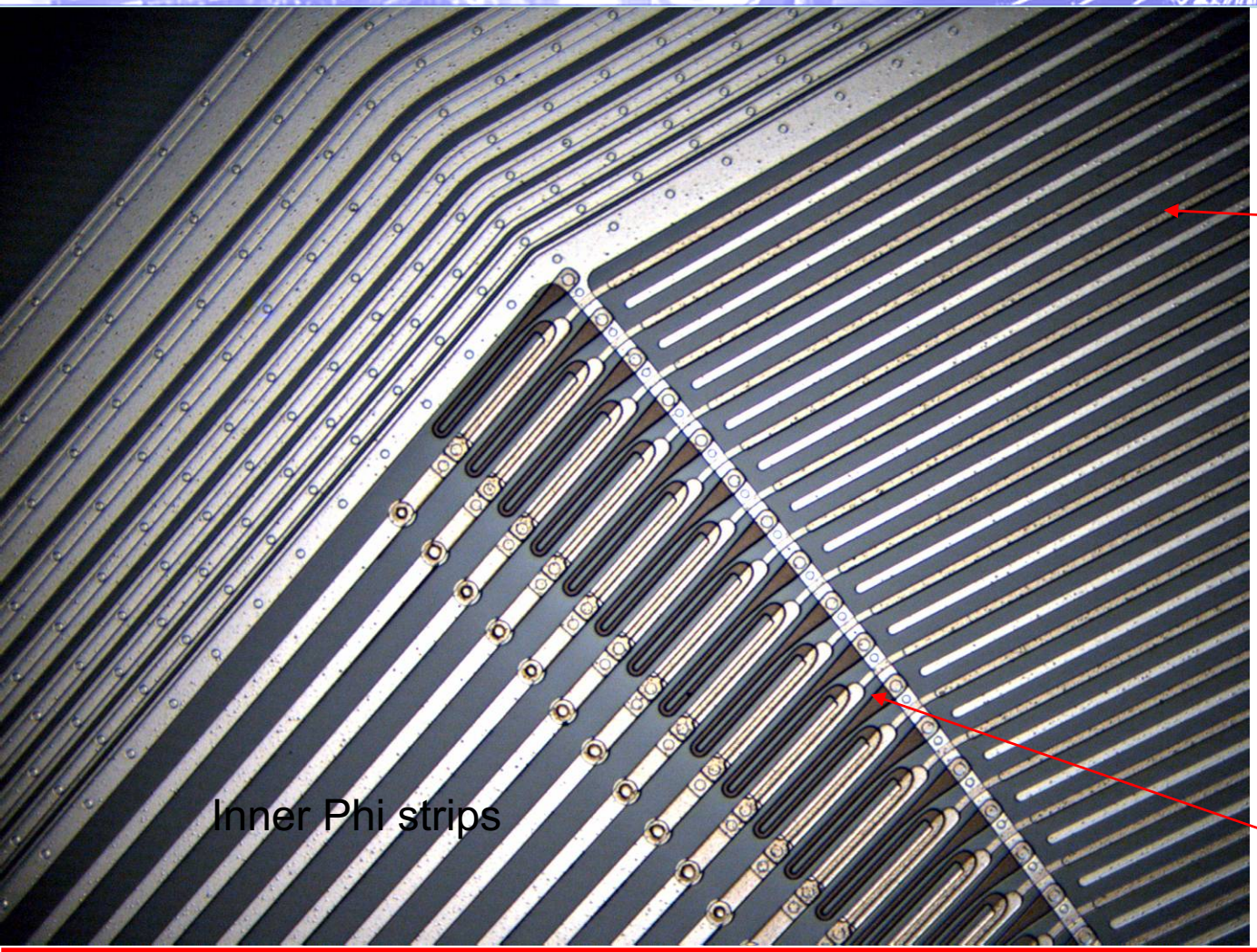




VELO: R-sensor

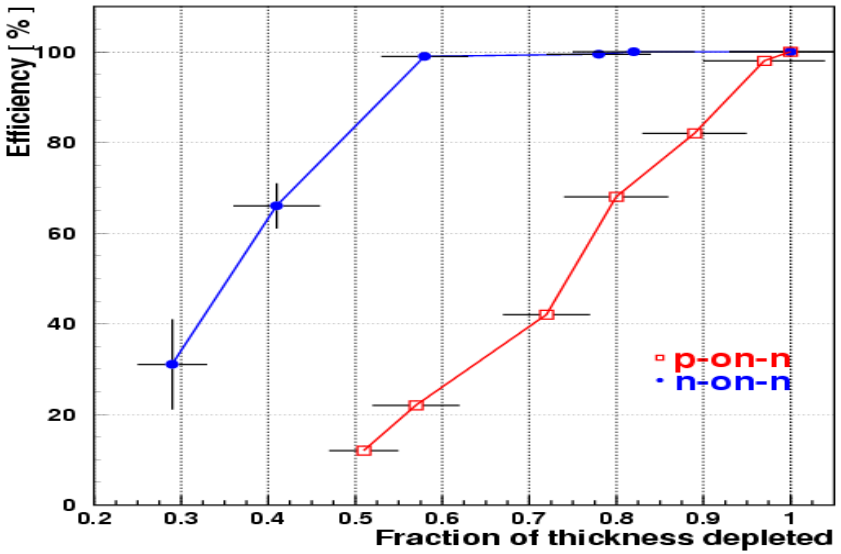


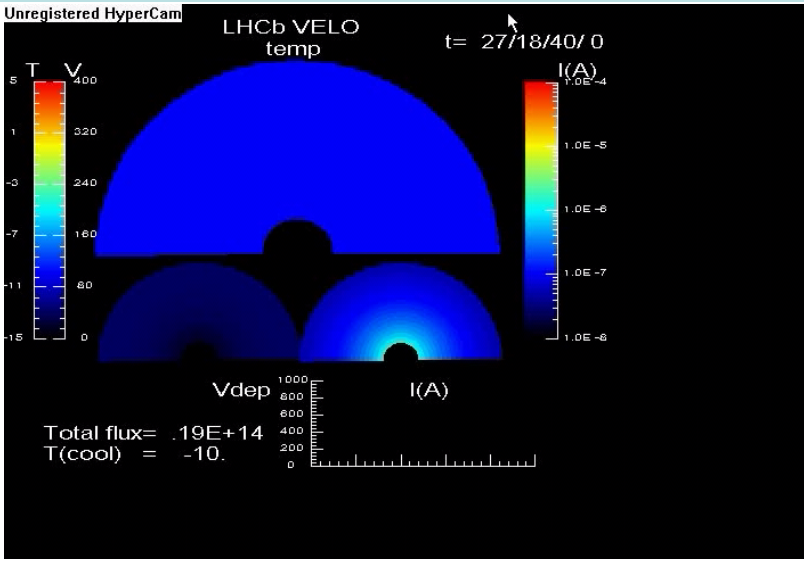
VELO: Phi Sensors



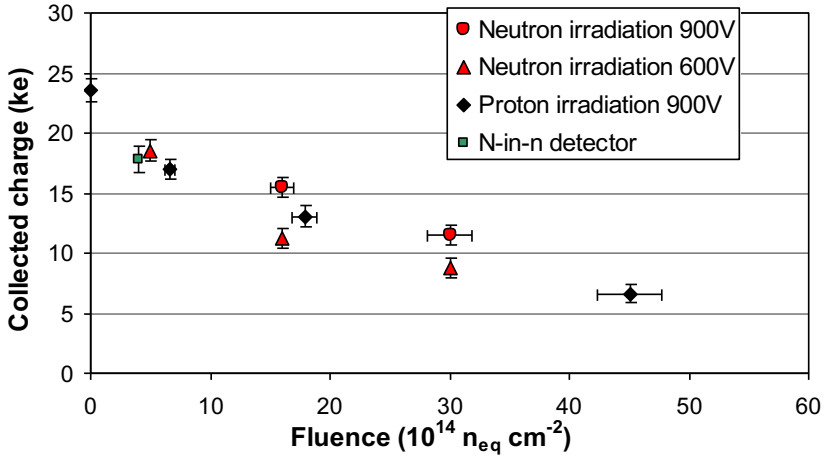
Sensor: Radiation Hardness

J. Libby, et. al. NIMA 494 (2002) 113-119





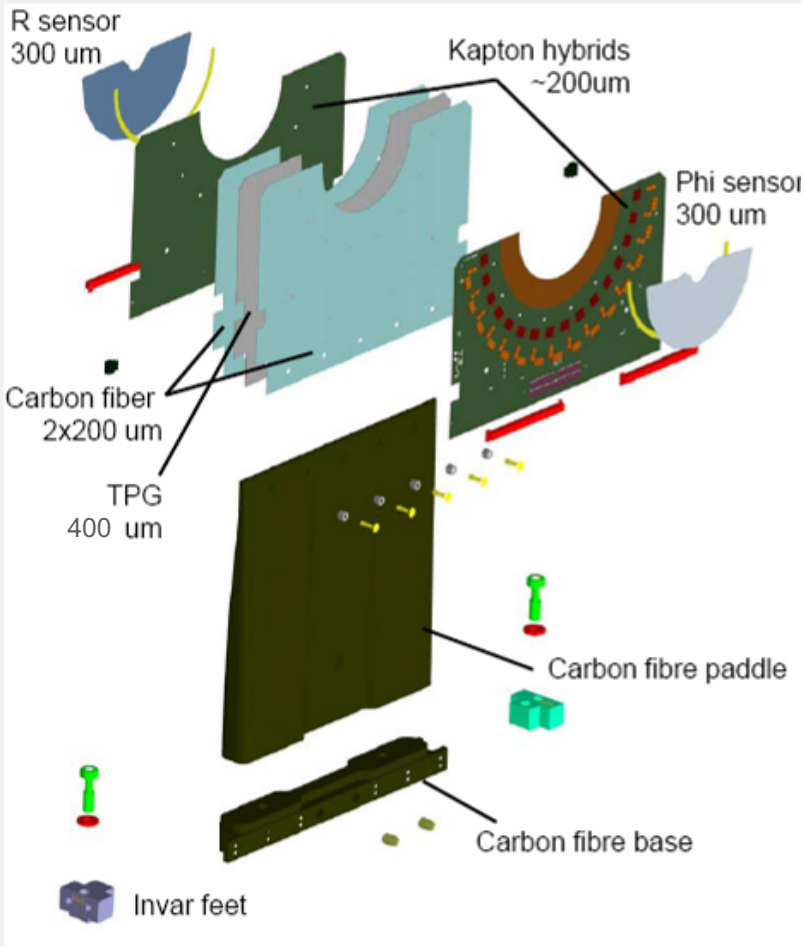
- After 3-4 years (6-8 fb^{-1}), the inner region of the sensor cannot be fully depleted
  - Dose estimates
    - 1.3 * 10^{14} neq/cm^2/year at R = 8 mm
    - 5 * 10^{12} neq/cm^2/year at R = 42 mm
- Running partially depleted, the estimated lifetime is > 6 fb^{-1}



MODULE CONSTRUCTION

CONSTRUCTION: Module

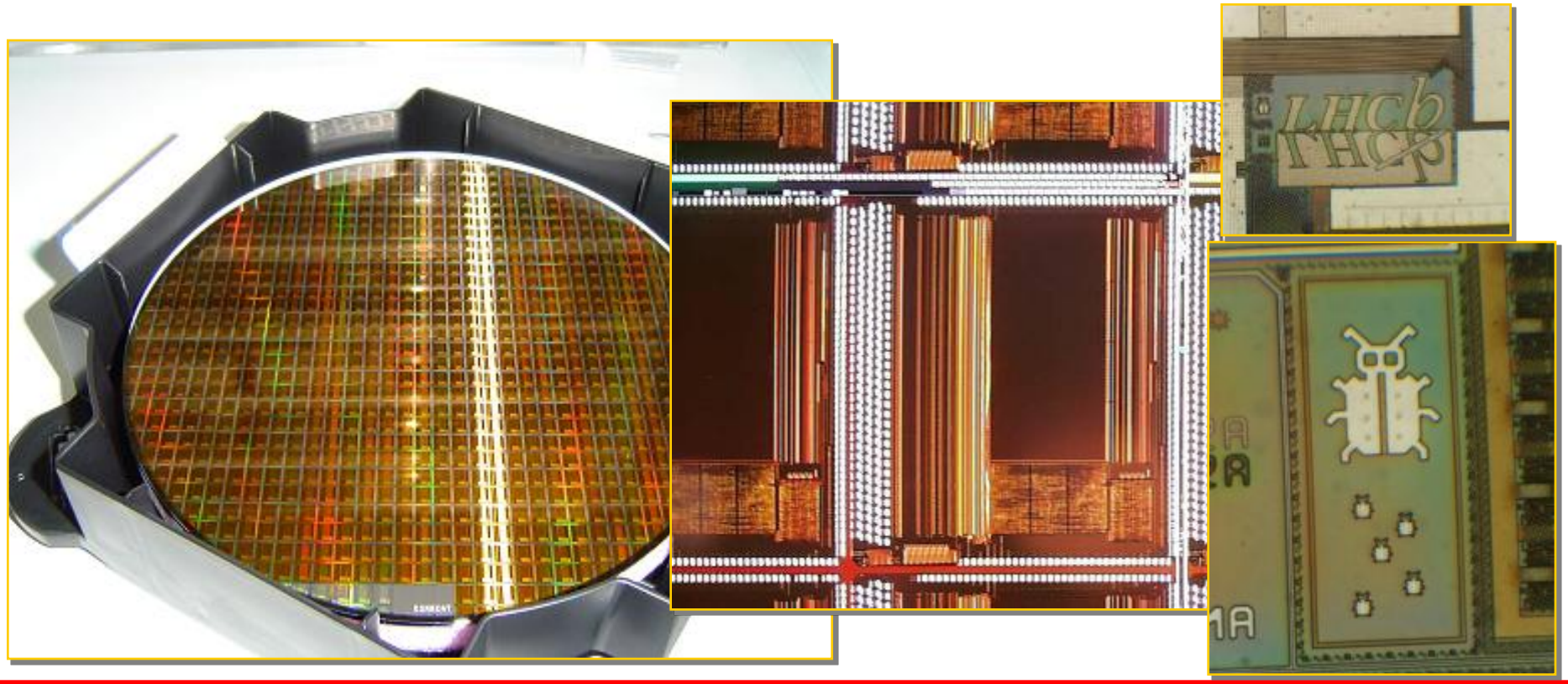
- 0 CTE assembly by design
  - -35°C to +30°C
- Compensated
- High precision
  - Si to 20 μm in space
- Vacuum (& rad)



CONSTRUCTION: ASIC Beetle

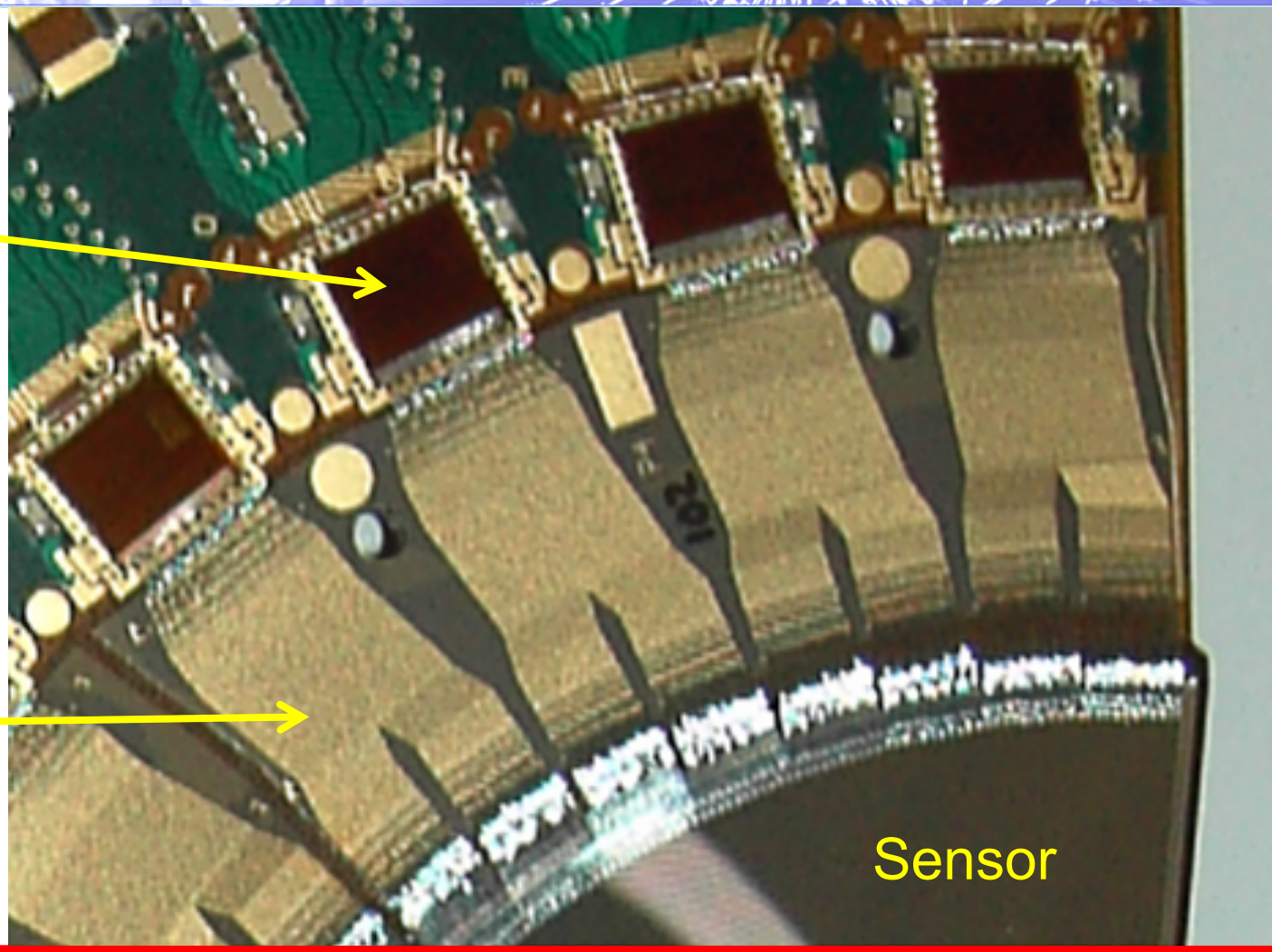
Design a new chip => the Beetle:

- 0.25 um CMOS ASIC
- Used in LHCb by VELO and ST

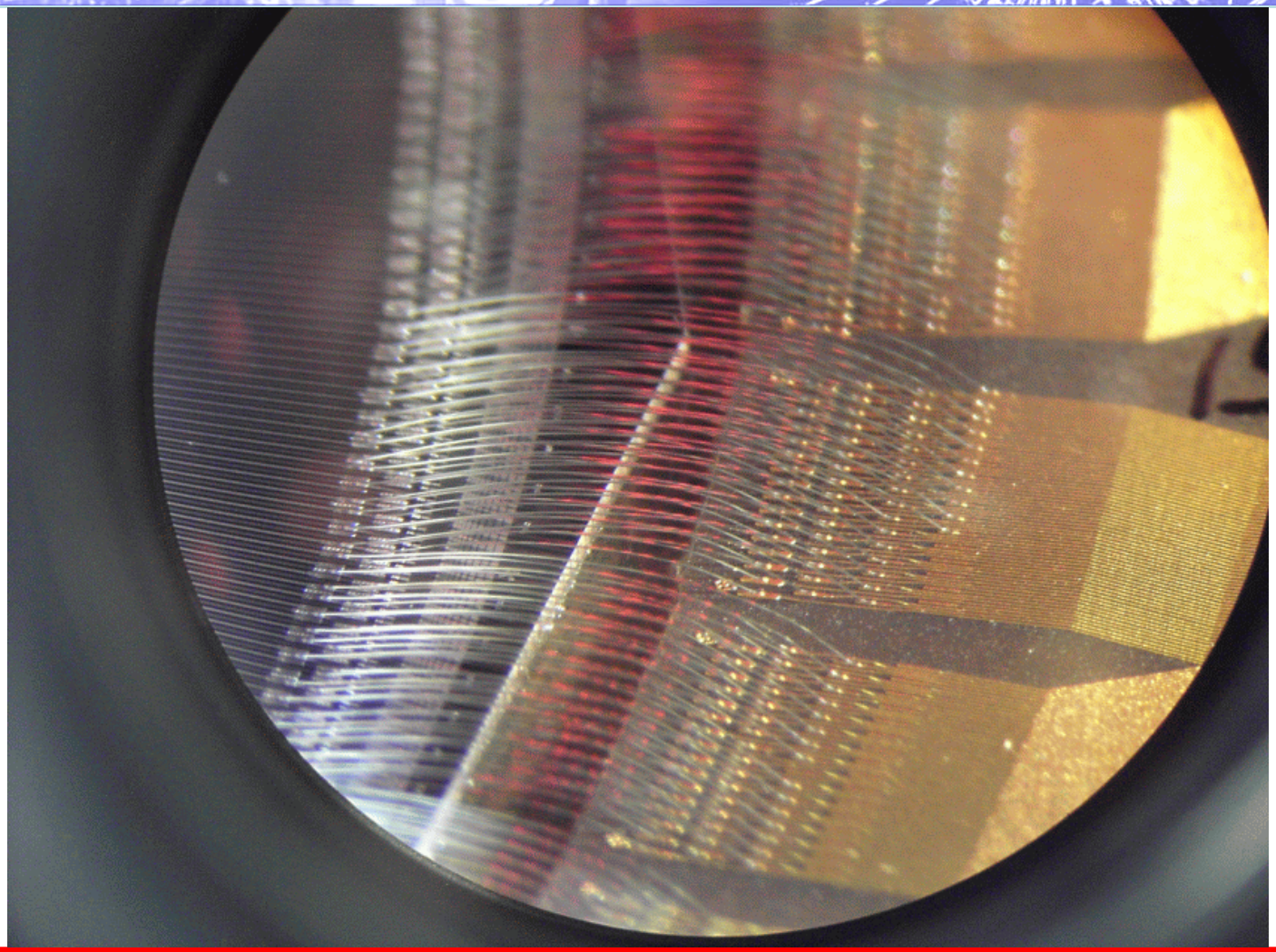


CONSTRUCTION: PA

- Beetle
- Kapton for mass

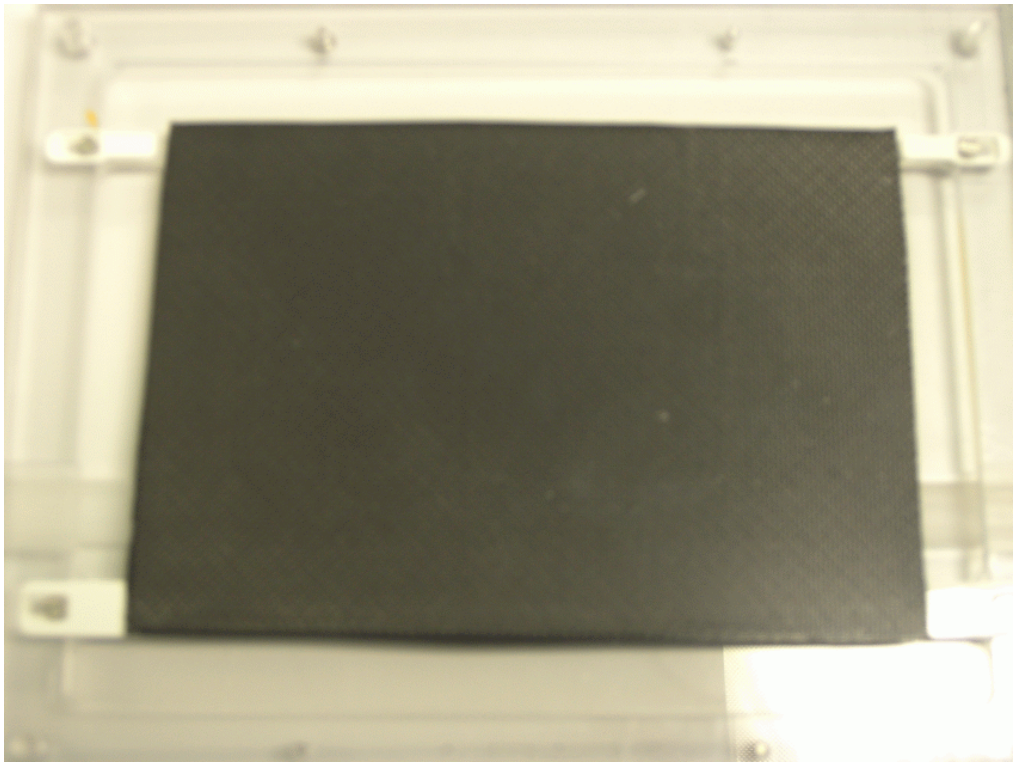


CONSTRUCTION: Bonding

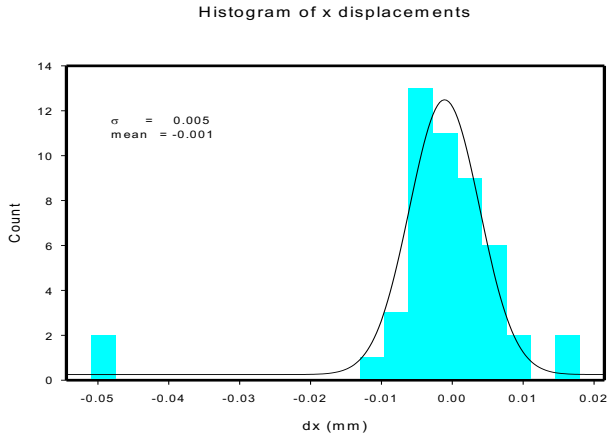


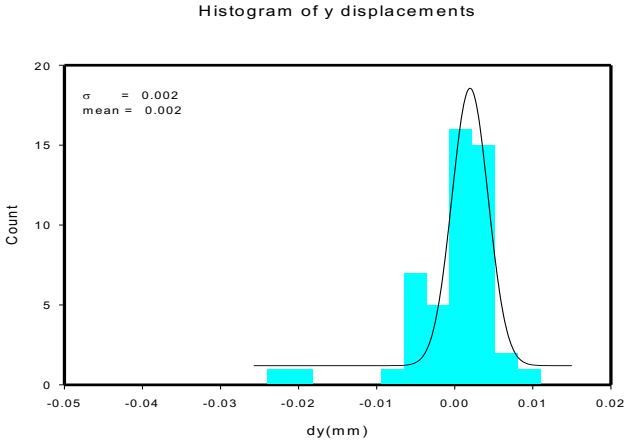
CONSTRUCTION: Hybrid

- TPG/CF core
- Double sided
- Populated
- Pitch adaptors
  - Chips
- Bonding
- Sensors
- More bonding

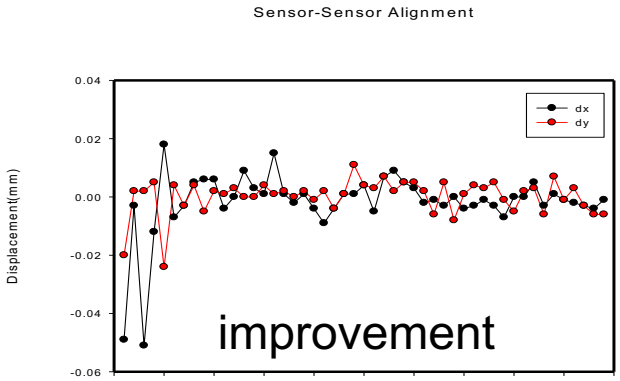


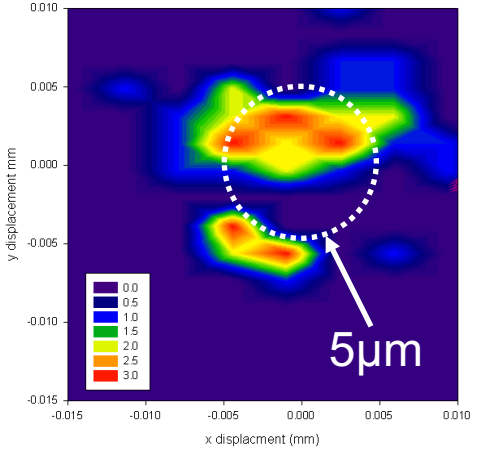
CONSTRUCTION: Alignment





Sensors placed very accurately with Respect to each other

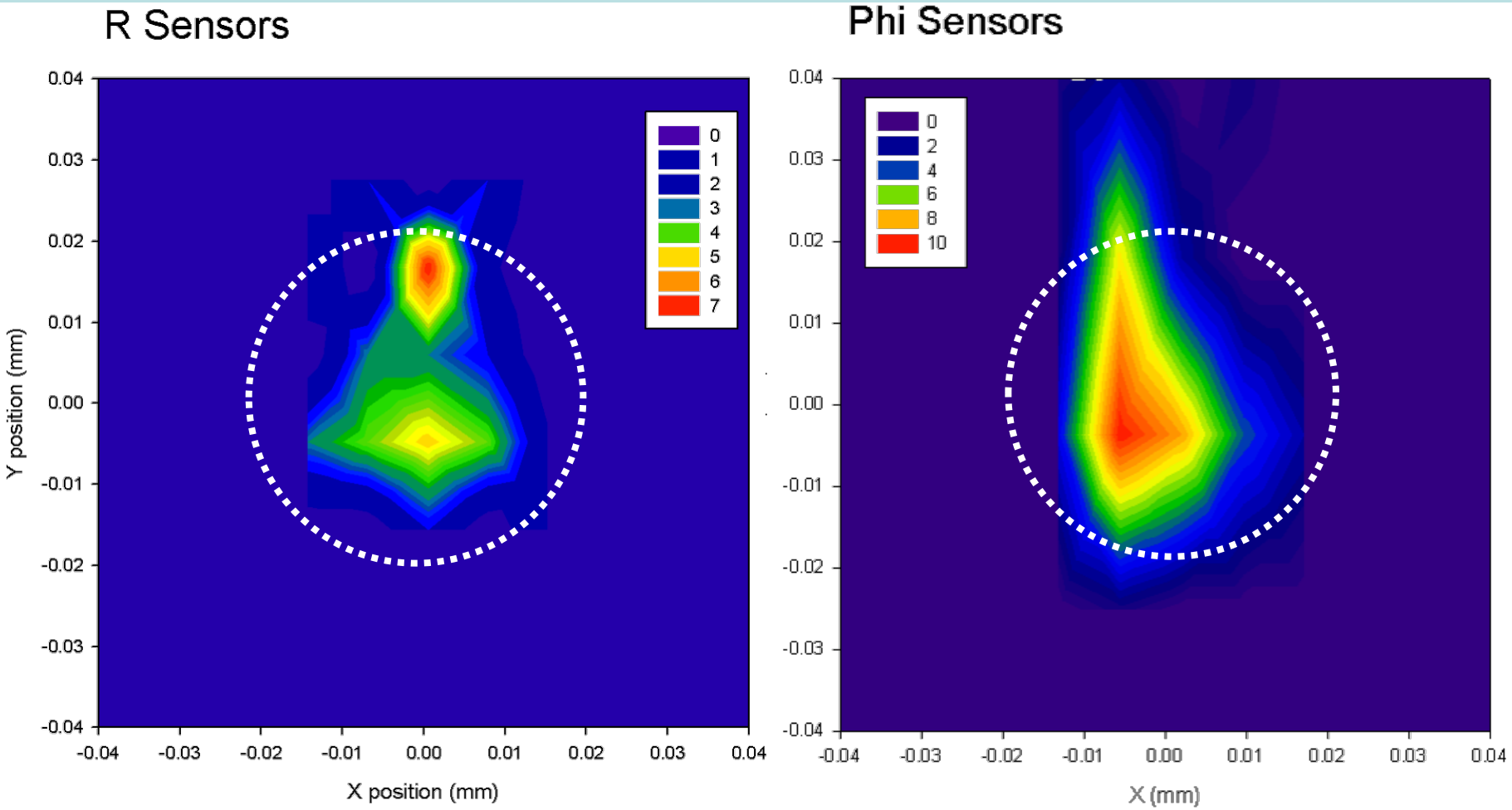




CONSTRUCTION: Metrology

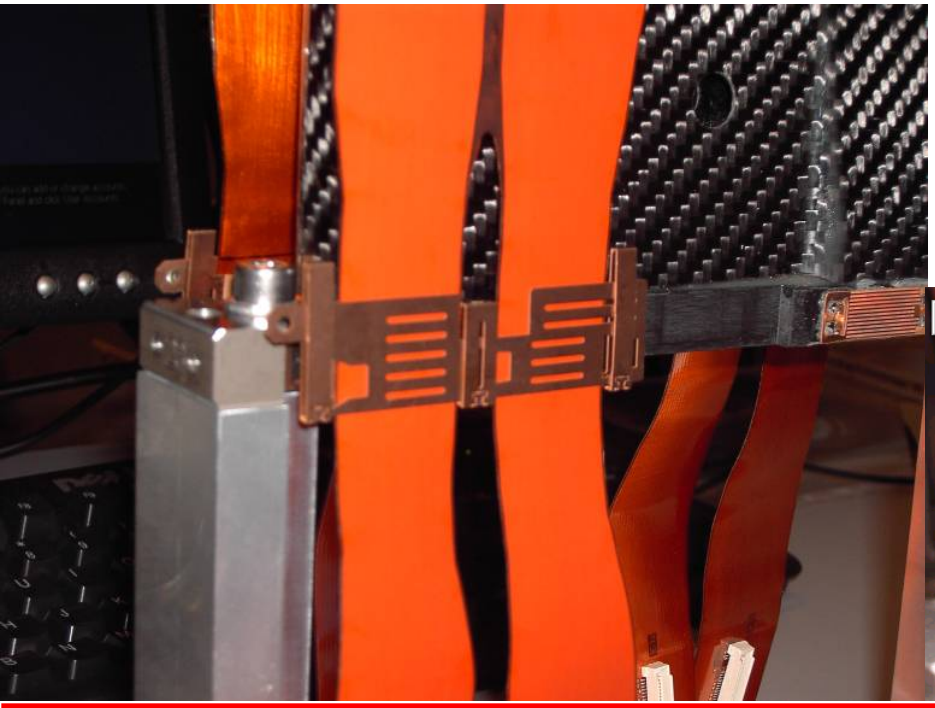
- CMM
  - **R-sensor (in trigger):**
    - Δx=-3±8 μm, Δy=6±13 μm $\Delta\theta$=-0.072±0.131 mrad
  - Phi-sensor:
    - Δx=-4±7 μm, Δy=7±19 μm $\Delta\theta$=-0.067±0.141 mrad

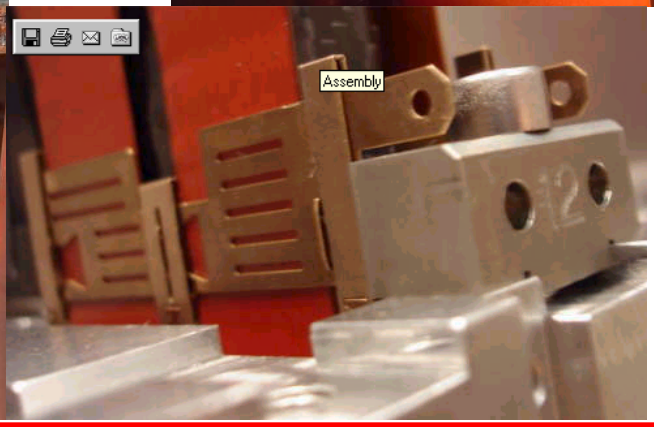
CONSTRUCTION: Metrology



CONSTRUCTION: Clamps

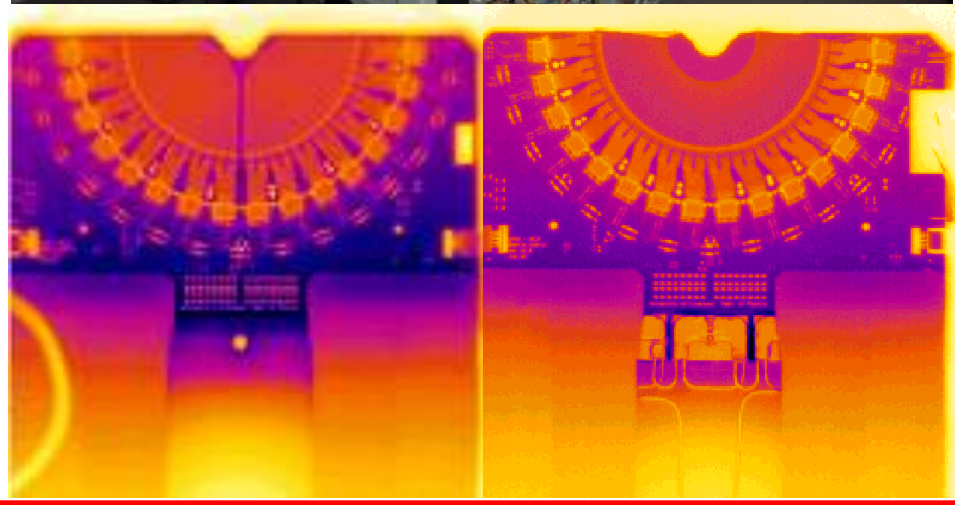
Clamps are used to relieve any stress on the modules caused by the cables, they are manufactured by Photofabrication.



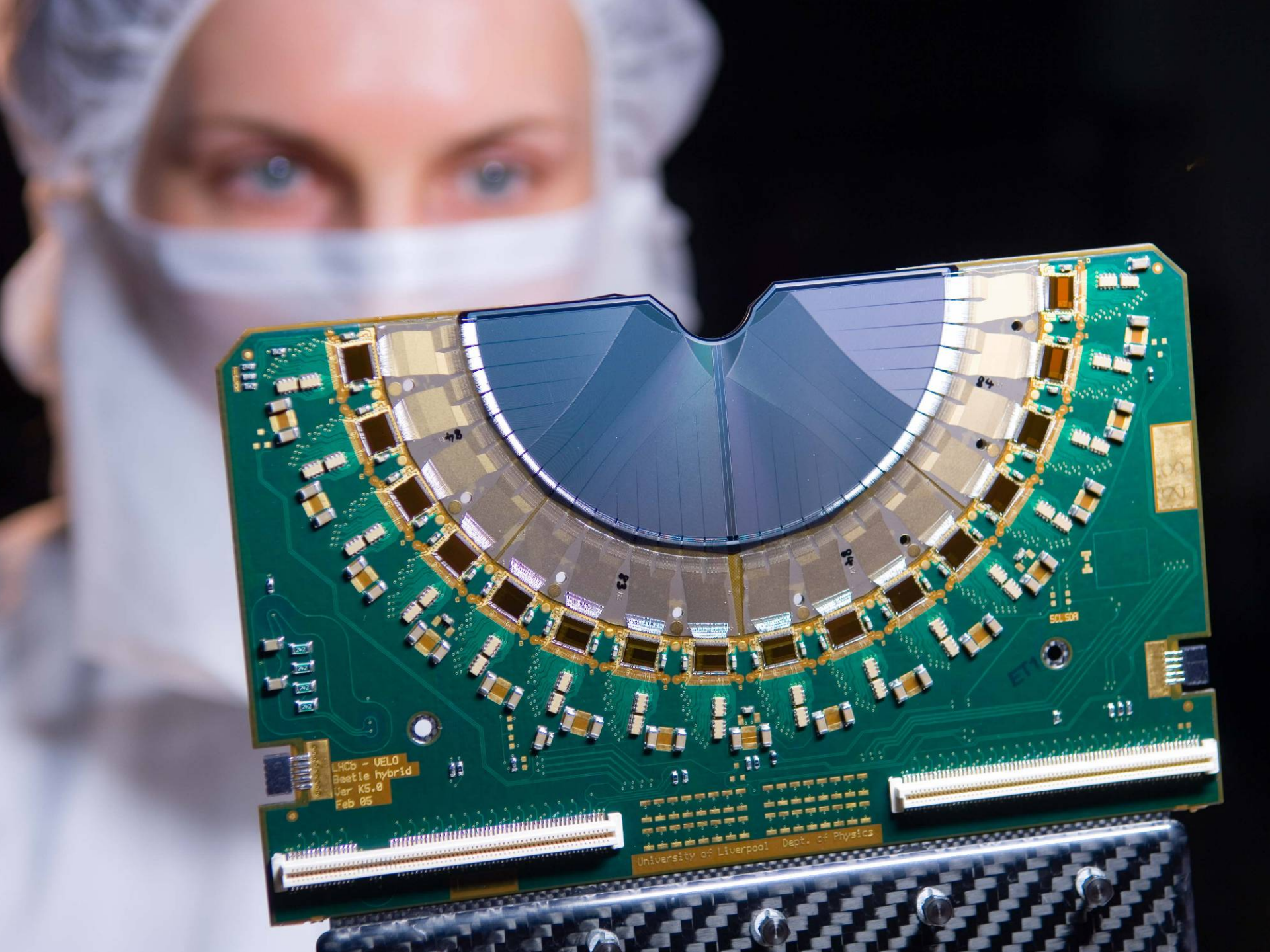


CONSTRUCTION: Burnin

- All modules tested in vac with near final CO_2 cooling system and DAQ
  - ~1x10^{-3} mbar with coolant at -30° C
- Thermal performance as expected
  - ΔT =-22.8° C between coolant and sensor
    - Should be 2-3° C less with cold neighbours
  - 2 modules had anomalous cooling performance and were rejected (4%)
- During cooling modules moved < 40microns in Z

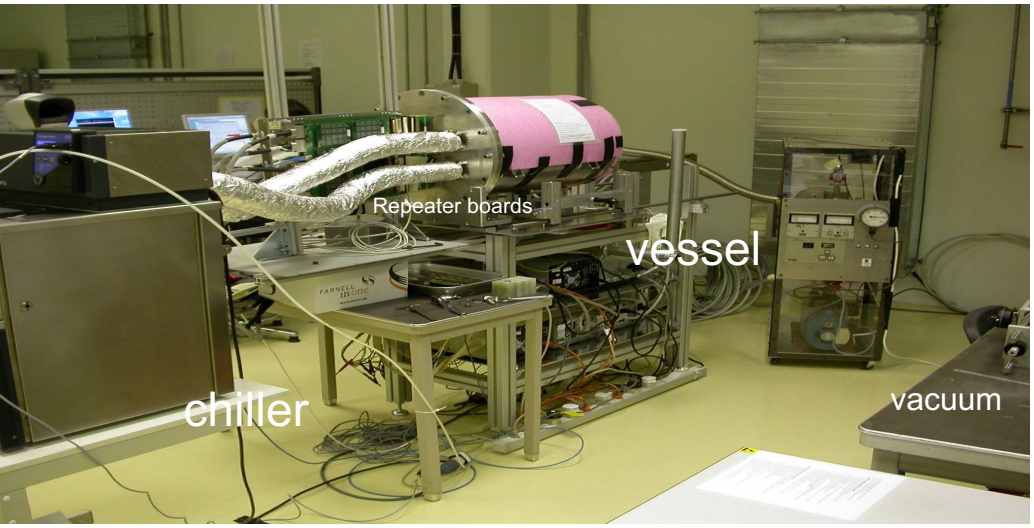


ASSEMBLY AND INSTALLATION


LHCb - VELO
Beetle hybrid
Ver K5.0
Feb 05
University of Liverpool Dept. of Physics

ASSEMBLY: Burnin at CERN

- Every module visually re-inspected on arrival at CERN
  - 3 hrs per module
- Module Burn-in
  - Electrical tests in vacuum (10^{-6} mbar)
    - Noise, pedestals, bias currents
  - Thermal stressing
    - 4 cycles between -30° C and 30° C
  - Electronics burn-in
    - >16 hrs at 30° C

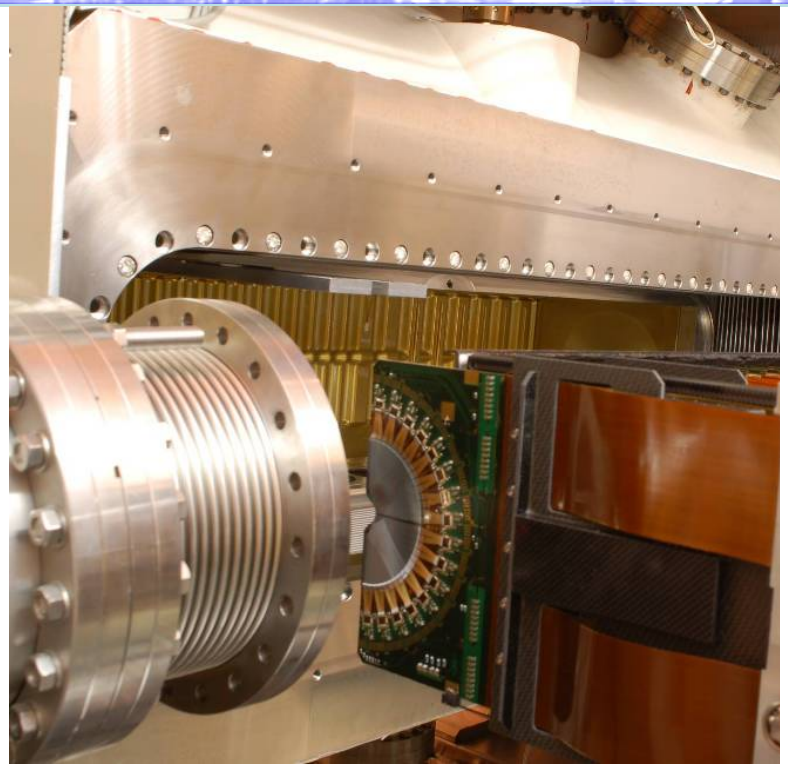



Only 41 to go …. !

ASSEMBLY: Complete halves

With constraint mechanism

INSTALLATION

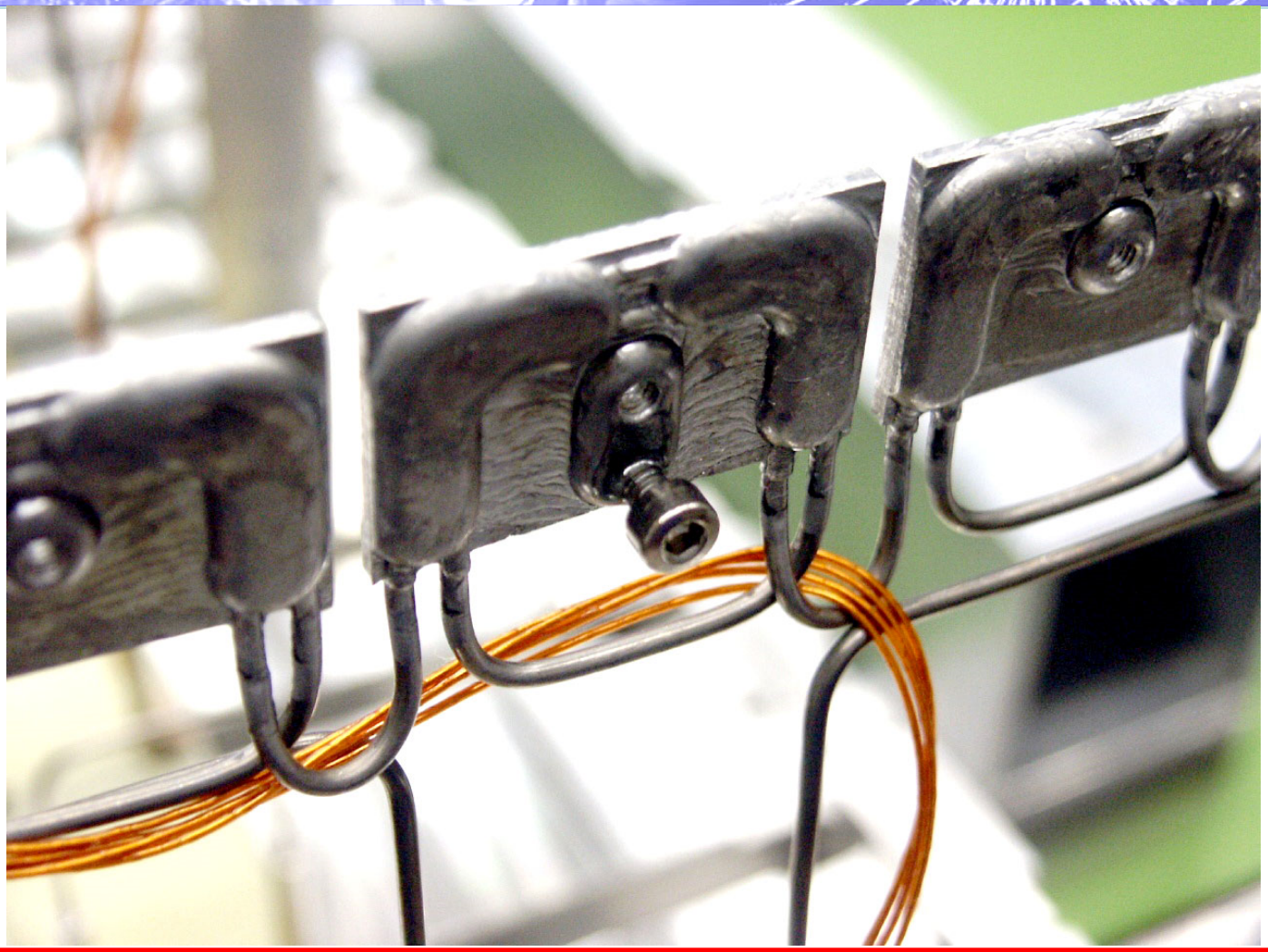


- After completion: testing I/V characteristics of modules

  → all OK

COOLING

COOLING



COOLING: CO2

Large latent heat & Low viscosity & High pressure

Allow low flow

Low pressure drop

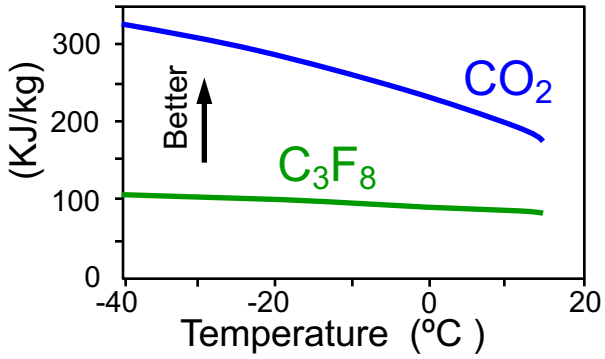
Low pressure drop

Lower pressure drop

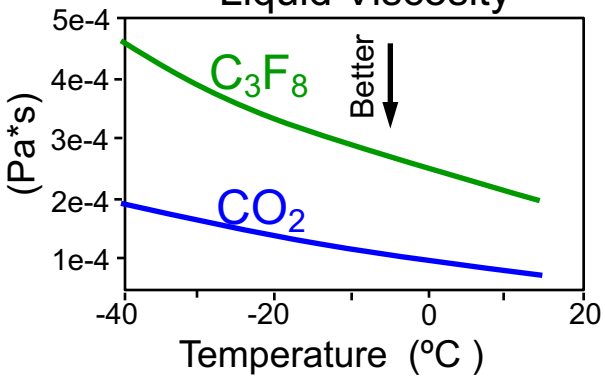
Allow high pressure drop

Allow very small tubing

Latent Heat of Evaporation



Liquid Viscosity

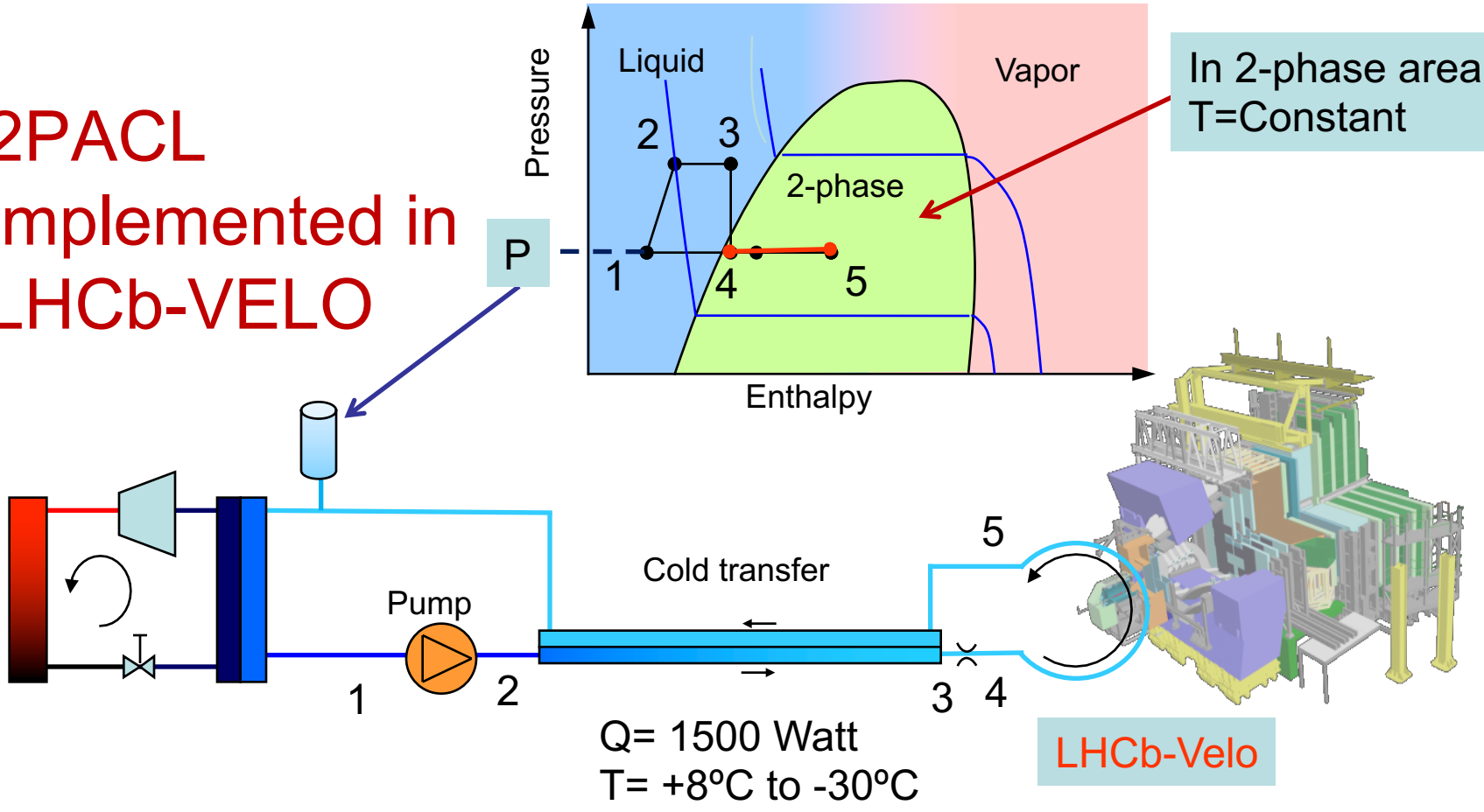


COOLING: Is CO_2 new?

- **NO!** it was used in the late 19th and early 20th century and is one of the first used refrigerants.
- The high pressure of CO_2 (130 bar) was a problem for materials those days.
  - Development of low pressure synthetic refrigerants (CFC's) causing CO_2 to disappear as refrigerant.

COOLING: 2-Phase Accumulator Controlled Loop

- 2PACL implemented in LHCb-VELO



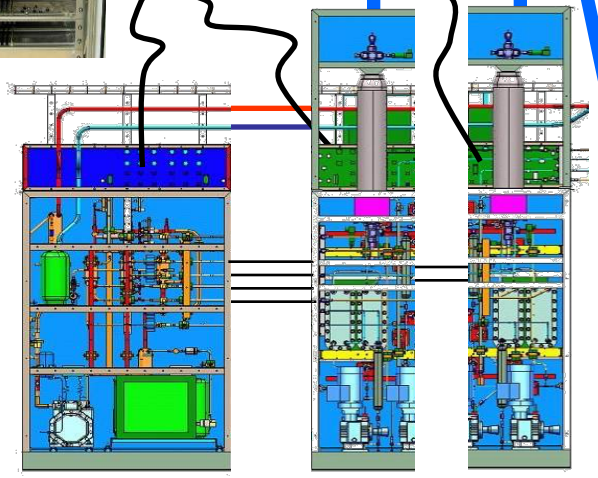
The LHCb-Velo Thermal Control System

Accessible and a friendly environment

Inaccessible and a hostile environment

4m thick concrete shielding wall

PLC



Passive hardware only

2 R507A Chillers:
1 water cooled
1 air cooled

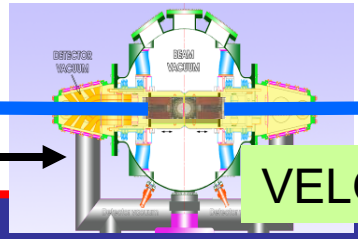
2 CO_2 2PACL's:
1 for each detector half

2 Evaporators
800 Watt max
per detector half

2 Concentric transfer lines

55 m

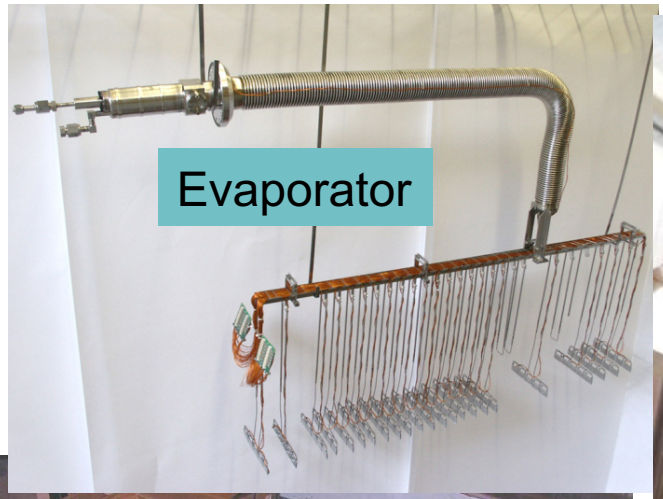
All the active hardware



VELO

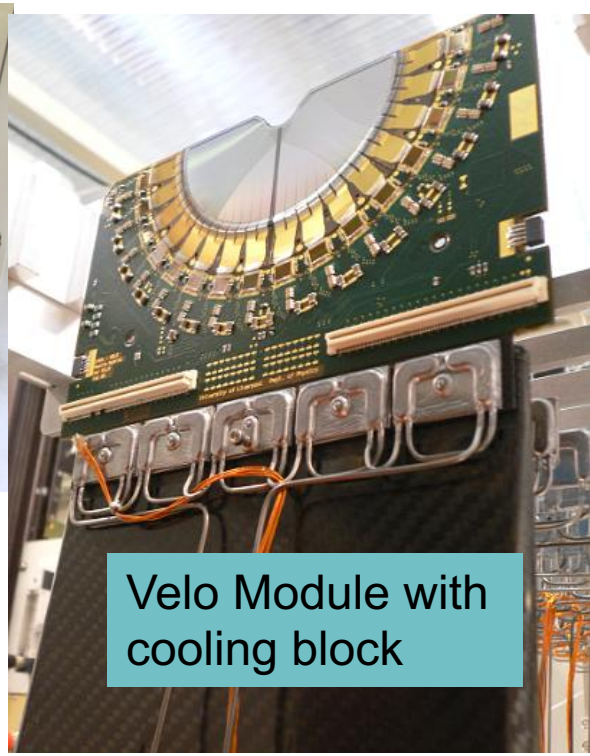
The LHCb-Velo Thermal Control System (LHCb-VTCS)

CO_2 rack



Evaporator

The VTCS cooling plant

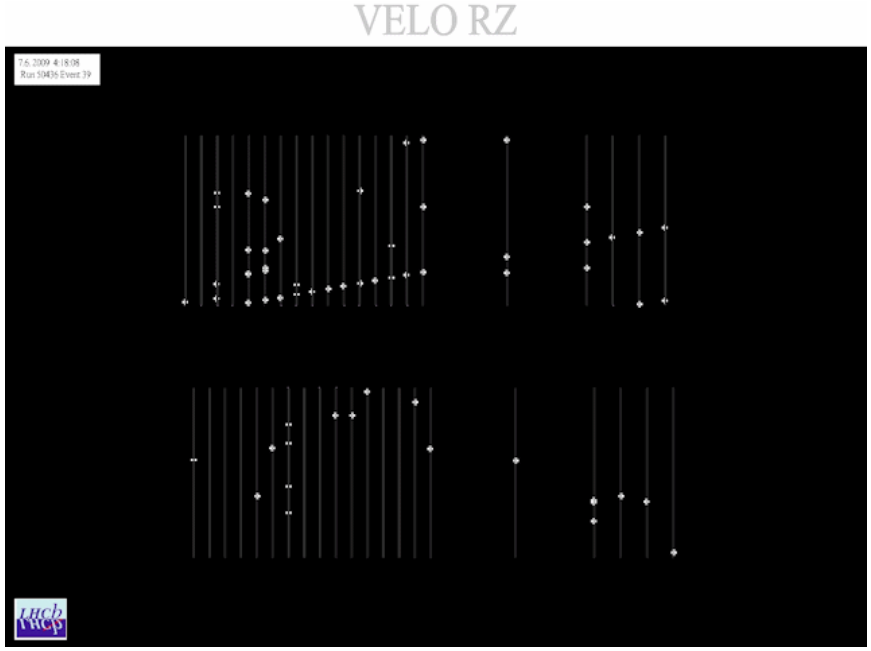


Velo Module with cooling block

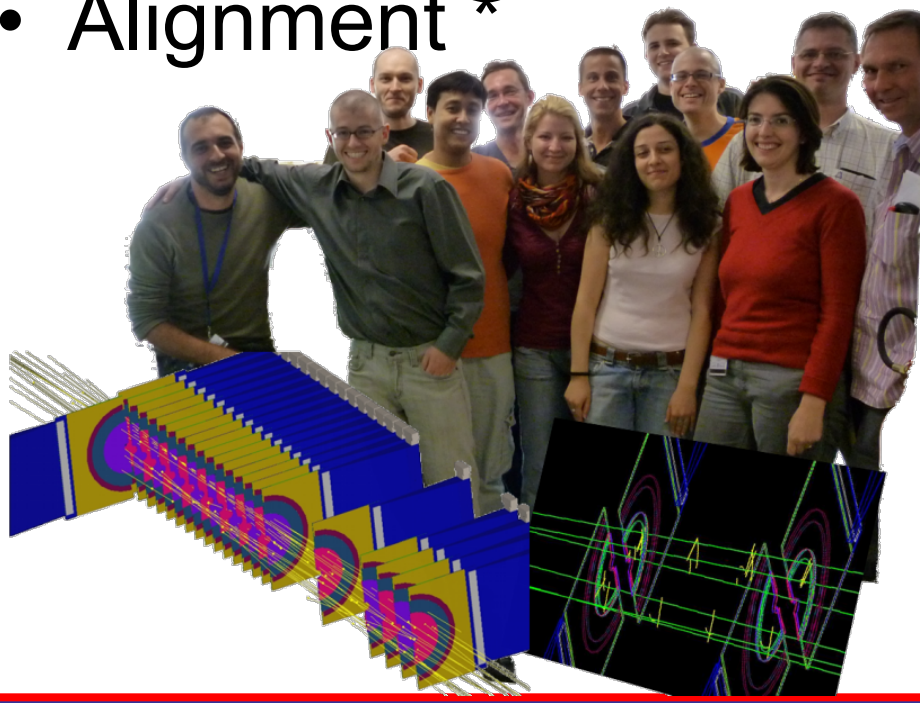
OPERATION & PERFORMANCE

TED June 2009

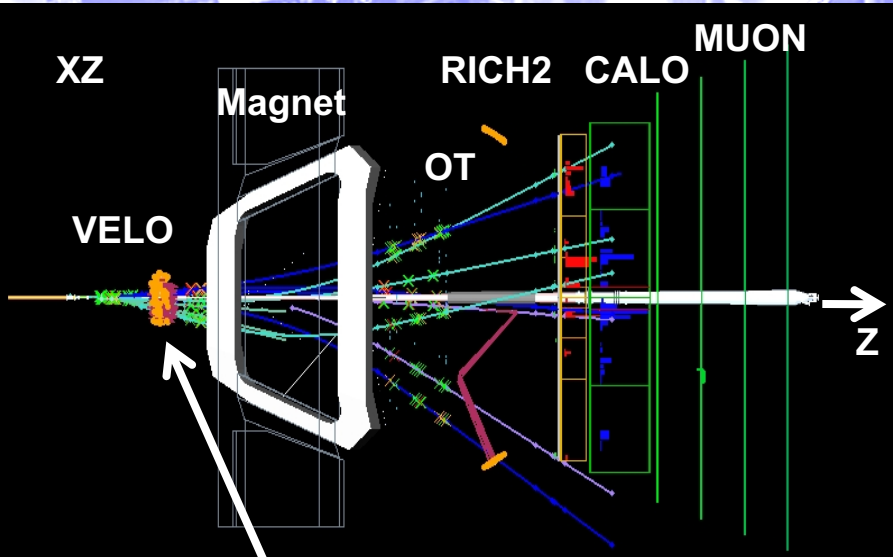
- 50k Tracks collected

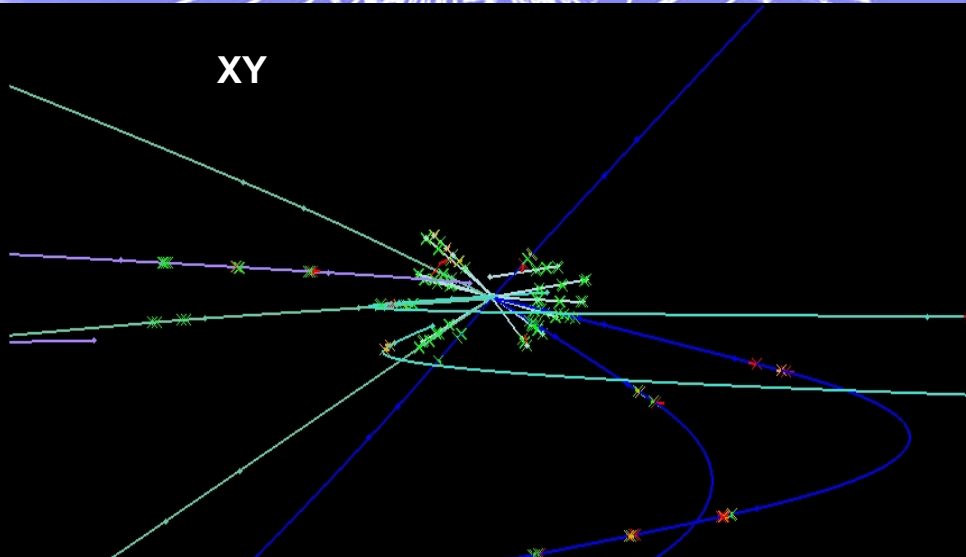


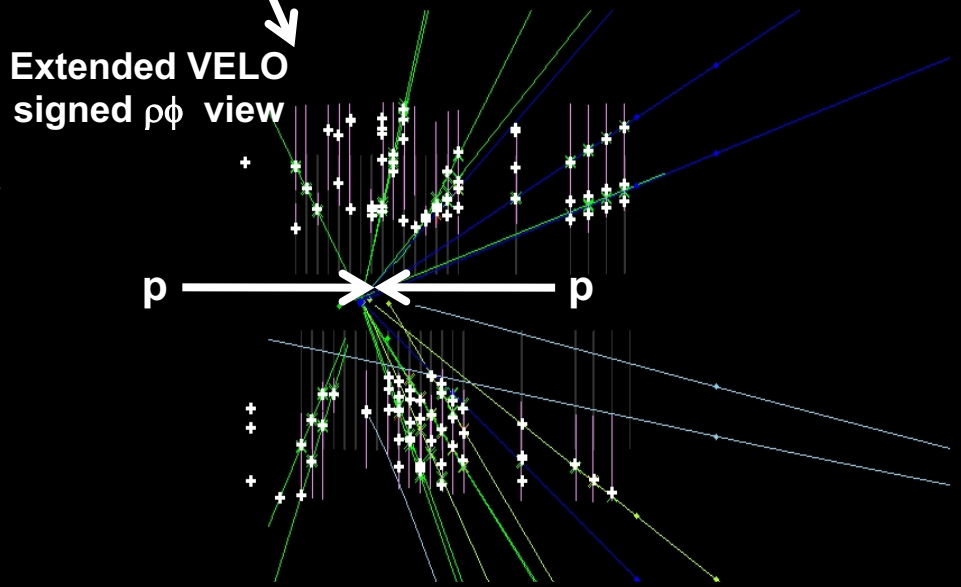
- Resolution
- Efficiency
- Alignment *

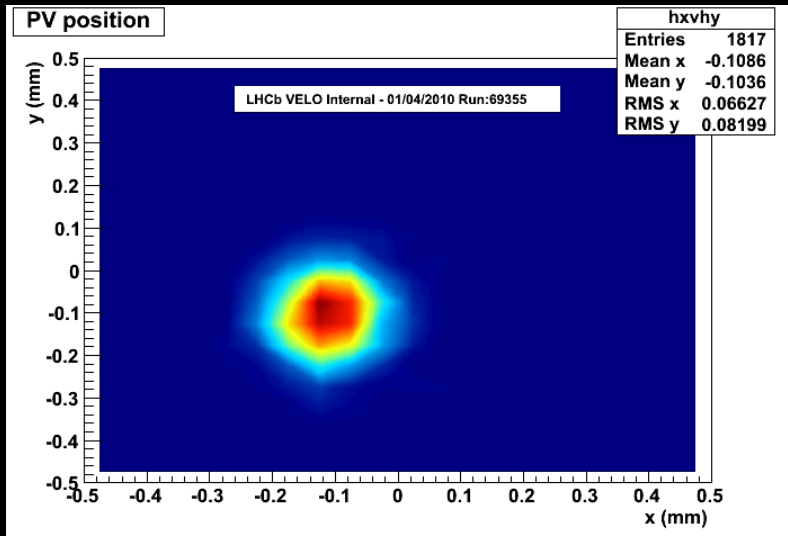


First Collisions 2009



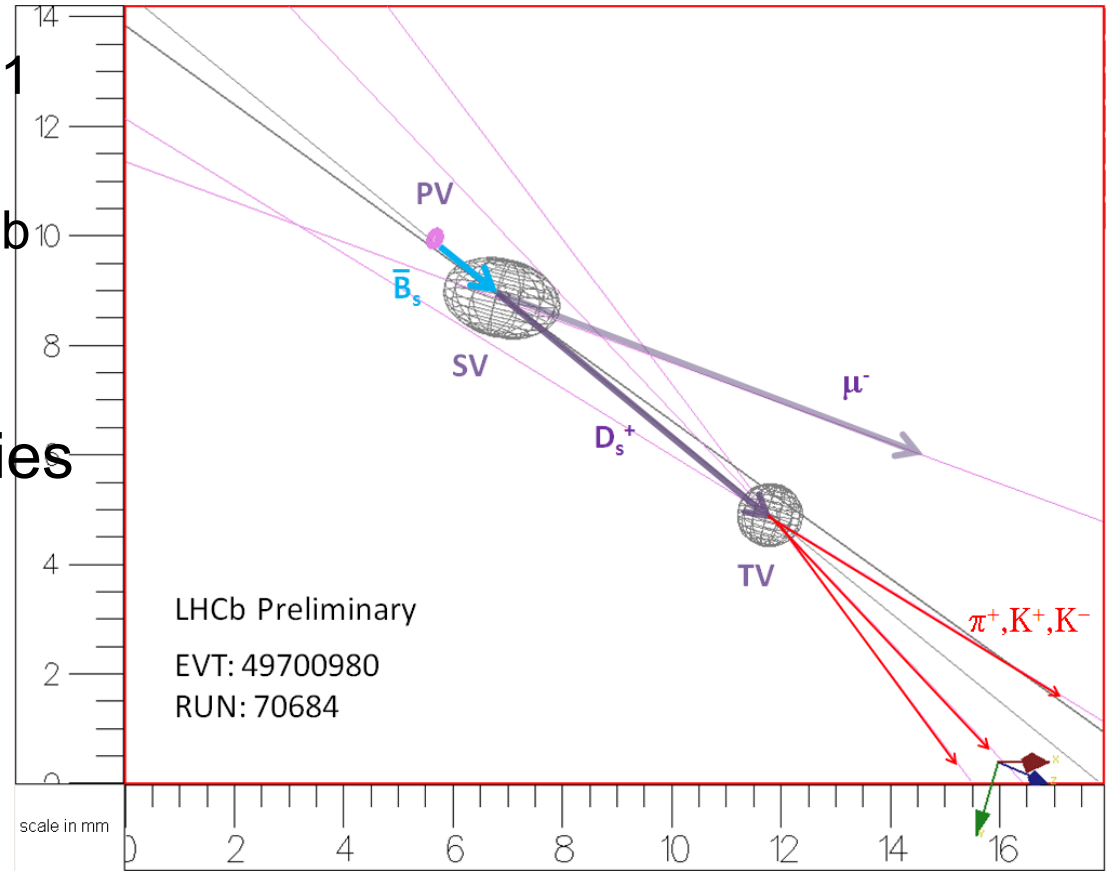




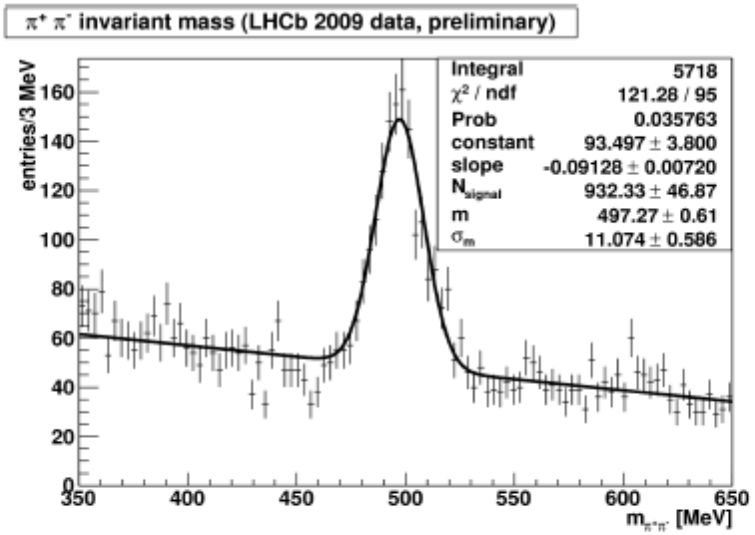


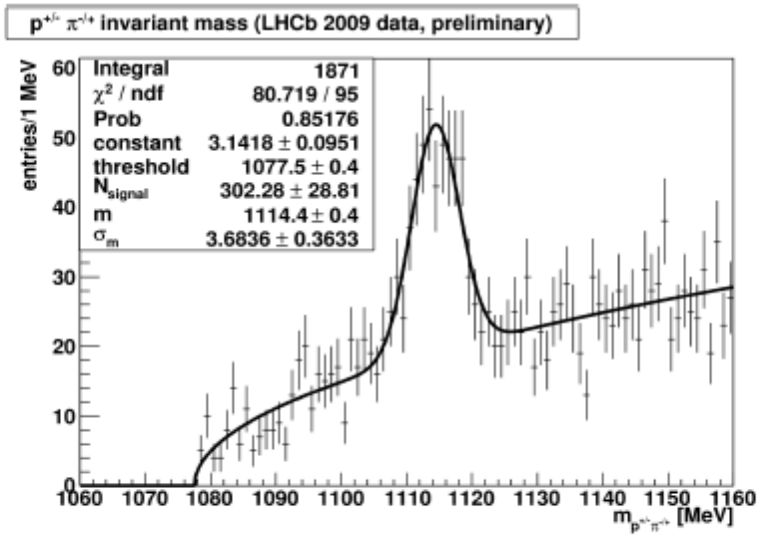
Summary

- VELO
  - Operated well from day 1
  - High Efficiency
  - Enables physics of LHCb
  - Expect to reach full potential in 2010
- Substantial challenge lies ahead with radiation damage ...



Earliest 2009 Data





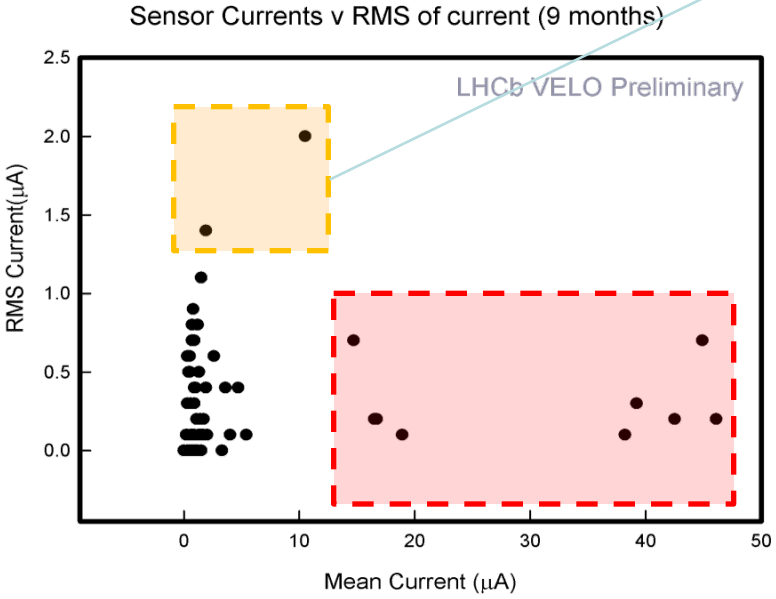
Manuel S., Sascha S.

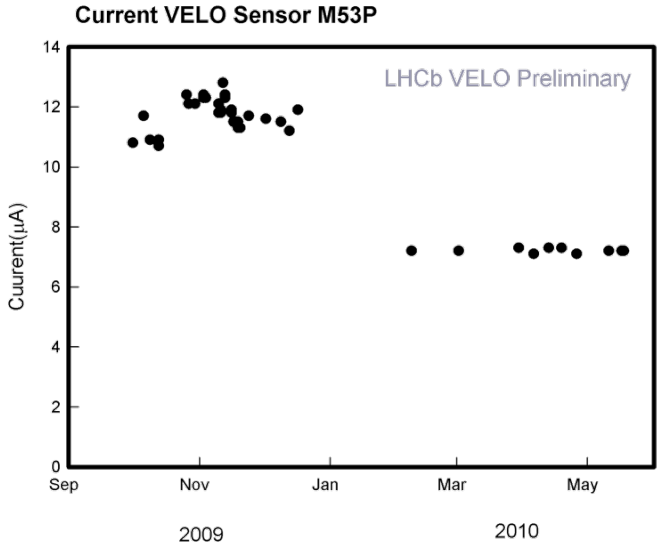
# 932 ±47
m = 497.3 ± 0.6 MeV
σ = 11.1 ± 0.6 MeV

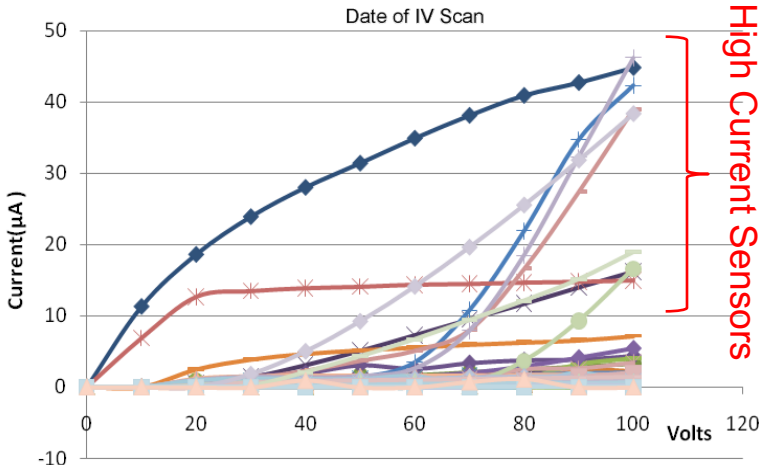
# 302 ± 29
m = 1114.4 ± 0.4 MeV
σ = 3.7 ± 0.4 MeV

PERFORMANCE: Silicon

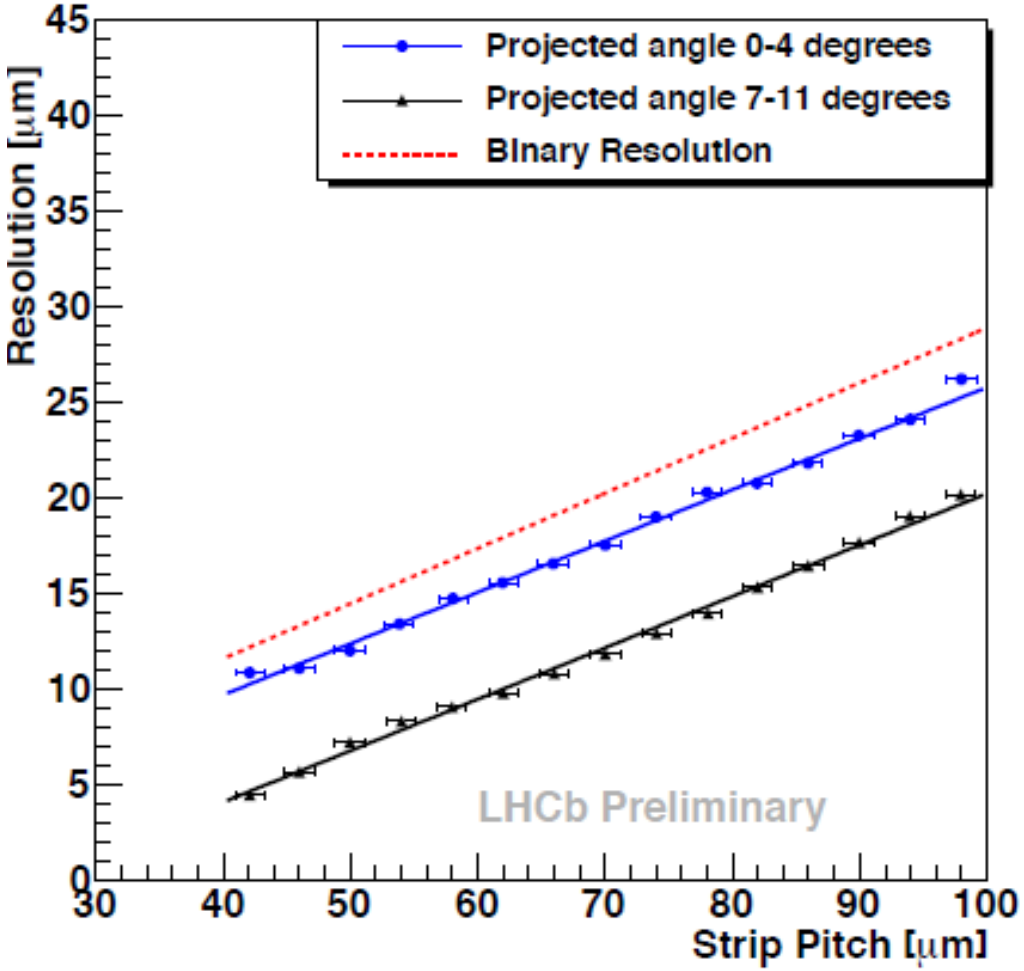
- No sign of Si changes
- IV scans run regularly
  - Currently use 100V as benchmark





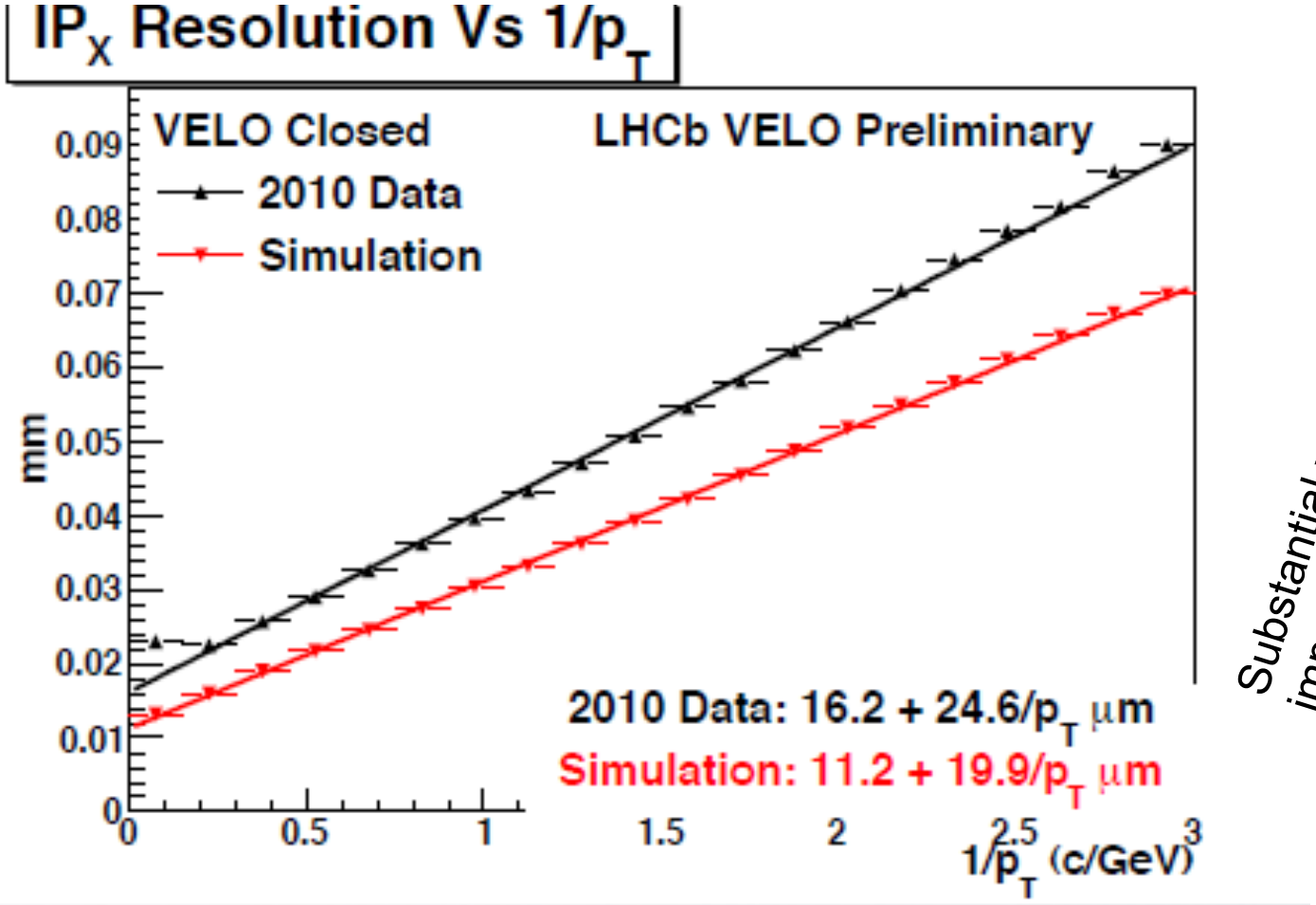


PERFORMANCE: resolution



Resolutions will improve

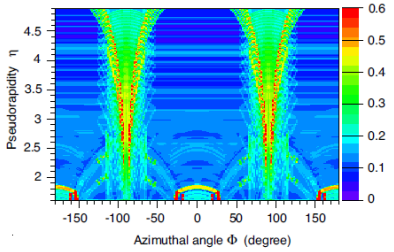
PERFORMANCE: IP Resolution

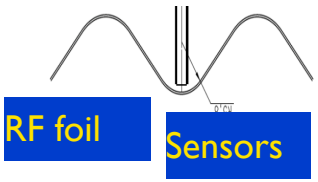


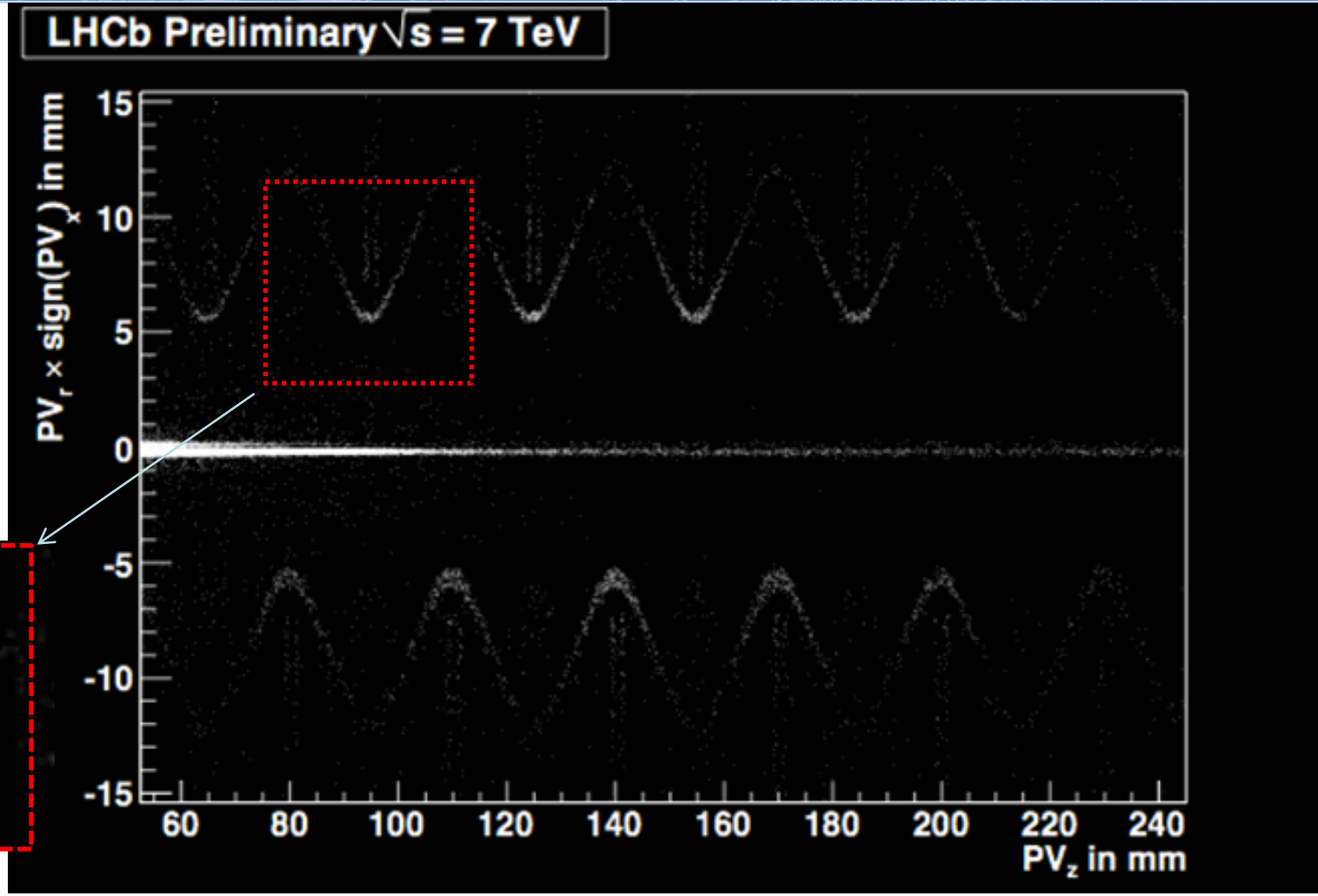
Substantial work remains to improve/optimize tracks

Much work underway

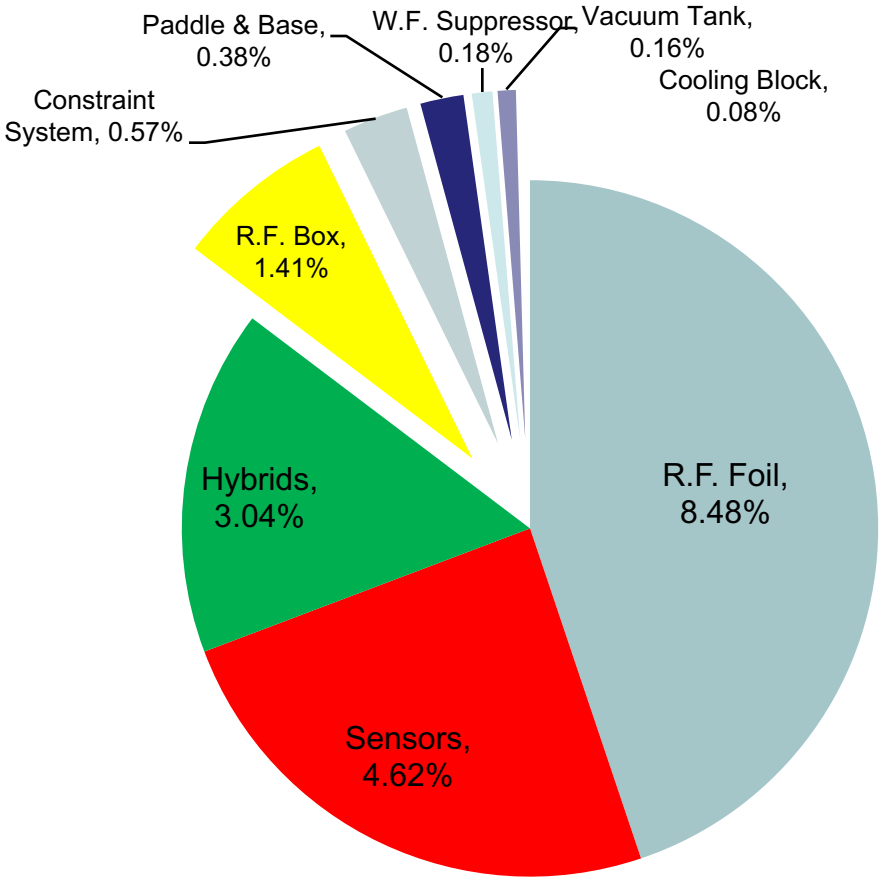
Material: Tomography





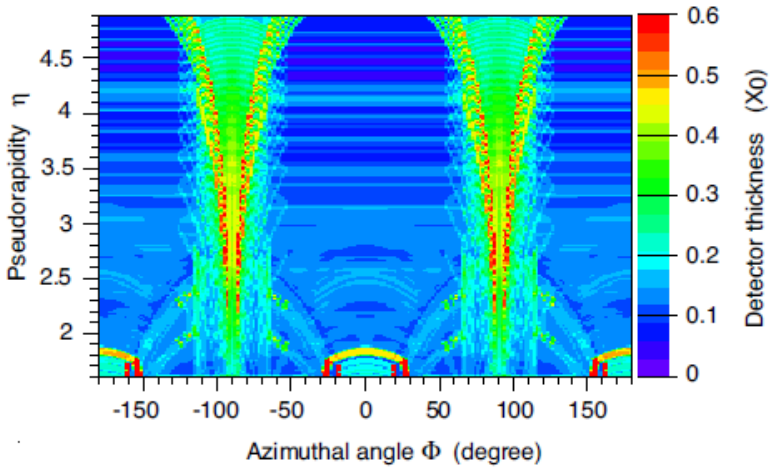


VELO: Material Budget



Material Budget (% X_o)

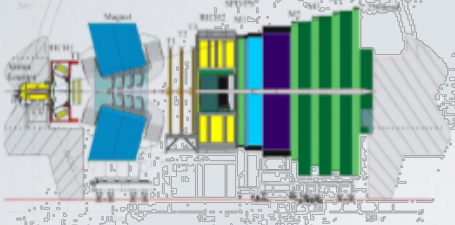
Average is 18.91% X_0
Particle exiting the VELO



Slides: S de Capua - Manchester

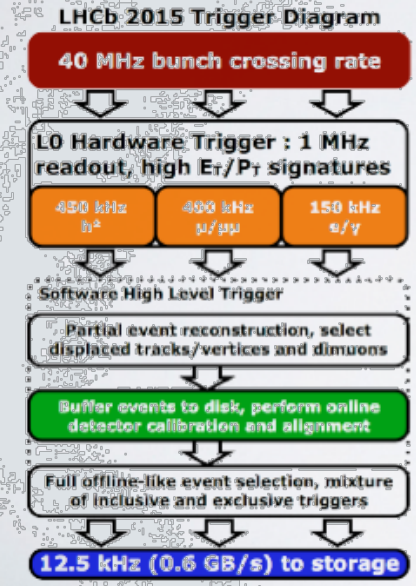
UPGRADE

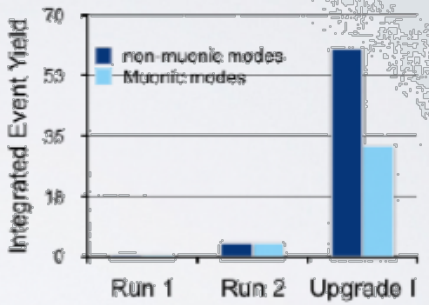
LHCb Upgrade motivation



Precision of many physics measurements at LHCb will be statistically limited at end of Run II:

- Increase luminosity to boost statistics:
  4×10^{32} cm^{-2}s^{-1} → 2×10^{33} cm^{-2}s^{-1}
- 50 fb^{-1} expected after LS2





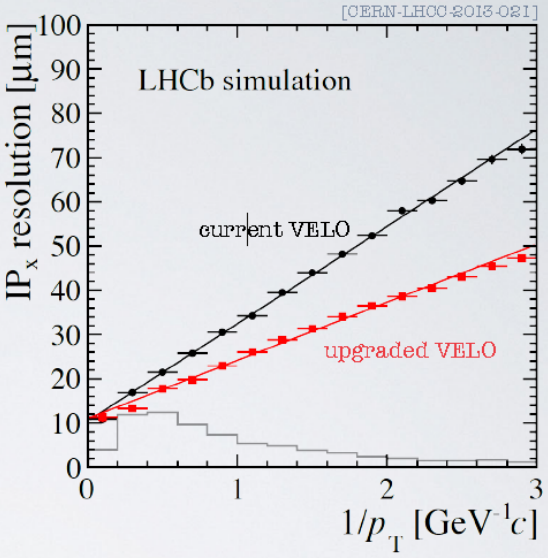
many hadronic channels saturate due to energy cuts in the trigger

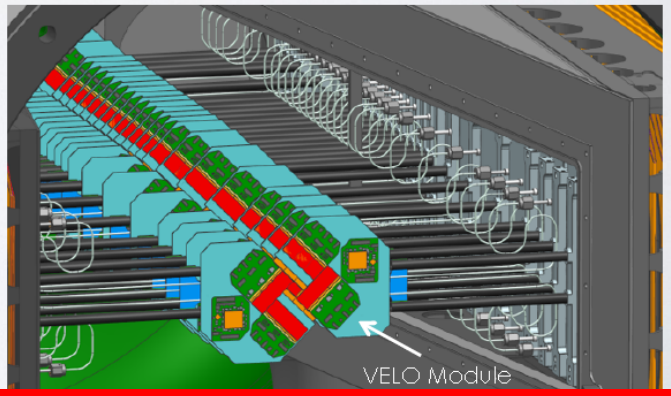
- Remove hardware trigger
- 1 MHz → 40 MHz readout rate
- Data taking starting in 2021 (Run III)

[CERN-LHCC-2012-007]

VELO Upgrade

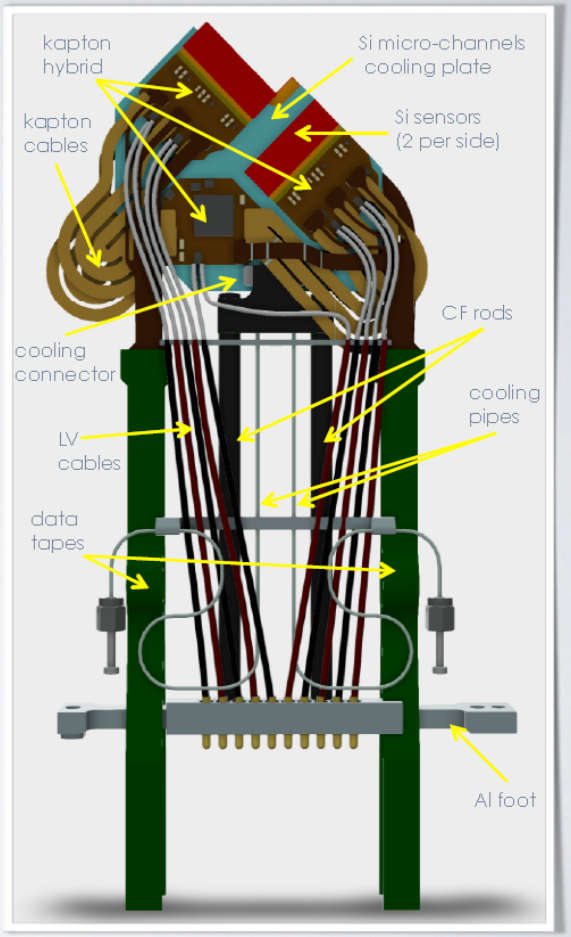
- To be operated @ 40 MHz and 2×10^{33} $cm^{-2}s^{-1}$ and at 3.5 mm from the beams
  - 2.8 Tb/s data rates
  - 8×10^{15} 1 MeV n_{eq} cm^{-2} max fluence
  - sensors to be kept < -20 °C
- Improve detector performance
  - track reconstruction
  - resolution
- The plan:
  - new pixel detector
    - no ghost tracks
    - faster reco algorithm
  - new front-end electronics
  - thinner RF-foil
  - more efficient cooling interface





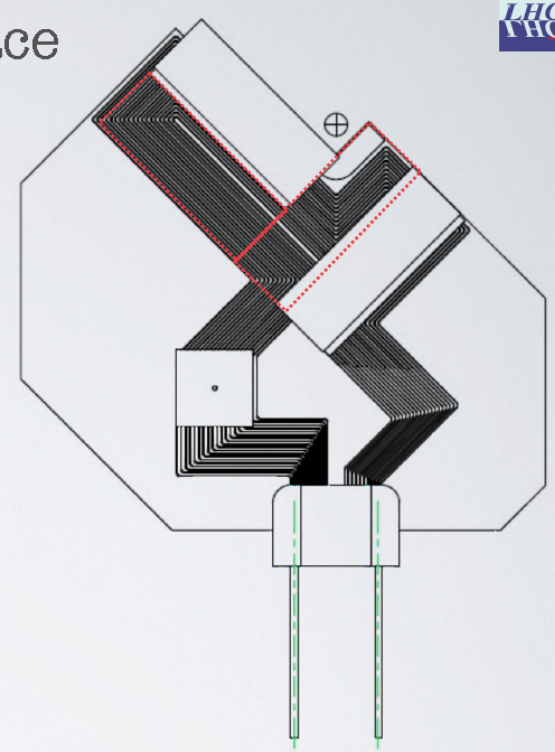
VELO Upgrade in numbers

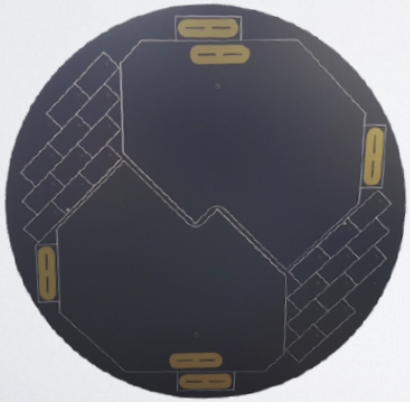
Feature	VELO	Upgrade
Sensors	R & φ strips 0.22 m² 172,032 strips electron collecting 300 μm thick 40-100 μm pitch	Pixels 0.12 m² **41 M pixels** electron collecting **200 μm thick** 55 μm pitch
# of modules	42	52
Max fluence	4.3×10^{14} MeV n_{eq} cm^{-2}	**8×10^{15}** 1 MeV n_{eq} cm^{-2}
HV tolerance	500 V	**1000 V**
ASIC readout rate	1 MHz	40 MHz
Total data rate	analog (eq. to 150 Gb/s)	2.8 Tb/s
Total Power consumption	1 kW	**1.6 kW** (30 W/module)



Micro-channel cooling interface

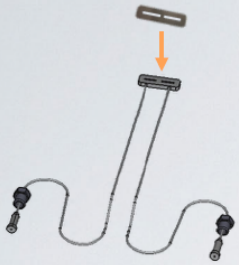
- 500 μm thick silicon substrate with integrated micro channels.
- same CTE as sensors + low material budget
- high thermal efficiency
- routing of channels customisable
  - 120 × 200 μm micro-channels (19×)
  - 60 × 60 μm high impedance restrictions
  - cooling power ~50 W
- pressure: 14 bar @ -30 °C, 60 bar @ 22 °C



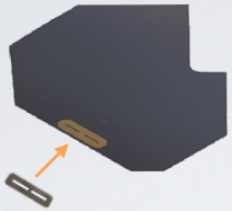


8" wafers containing 2 cooling interfaces, 4 soldering samples and several high pressure test samples.

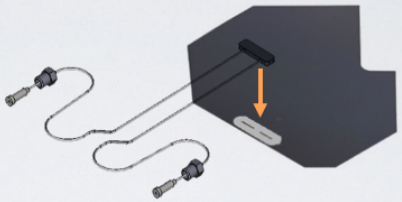
Micro-channel cooling interface



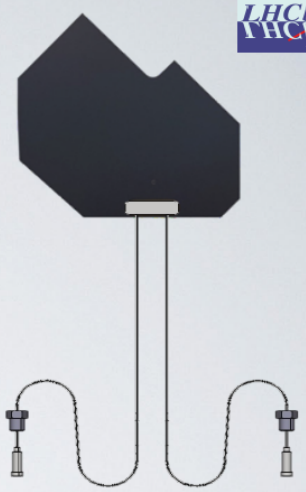
1. connector pre-tinning



2. silicon pre-tinning



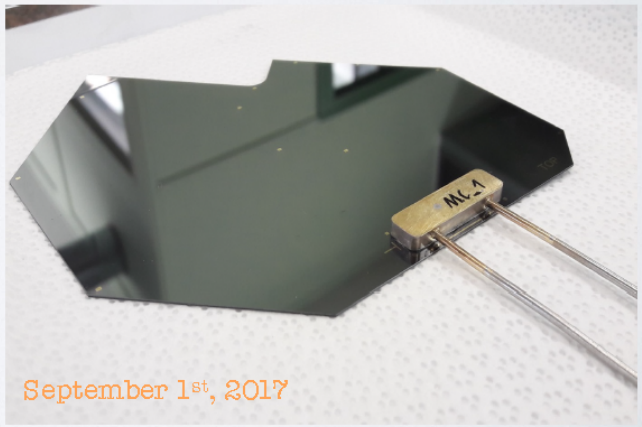
3. alignment



4. soldering

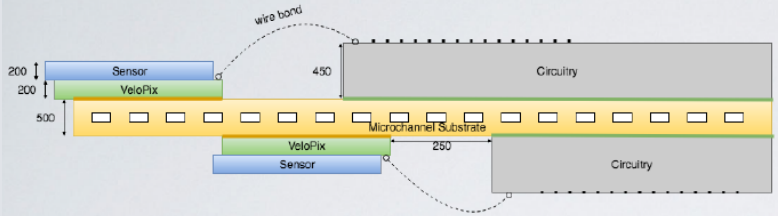
- high quality soldering is essential
  - leak tightness
  - planarity
  - minimum voids in the solder layer
  - no flux
  - high pressure qualification : 186 bar
- metallization with Ti+Ni+Au

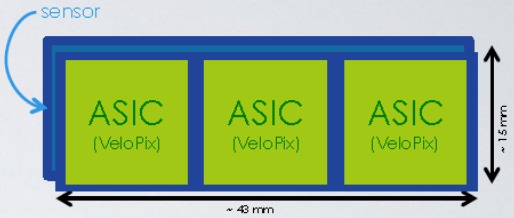
For more details see this talk.



September 1st, 2017

Sensors & ASICs: specifications



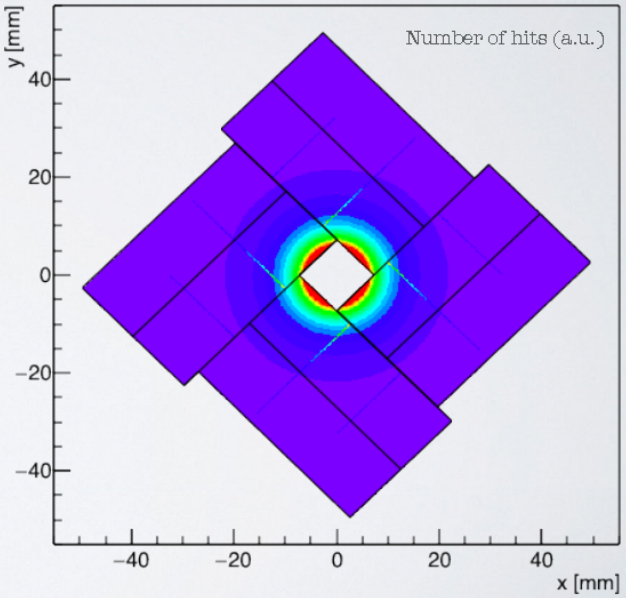


- ASIC derived from TimePix3 (VeloPix)
- 130 nm CMOS technology (TSMC)
- 256 x 256 pixels, 55 x 55 μm pixel size

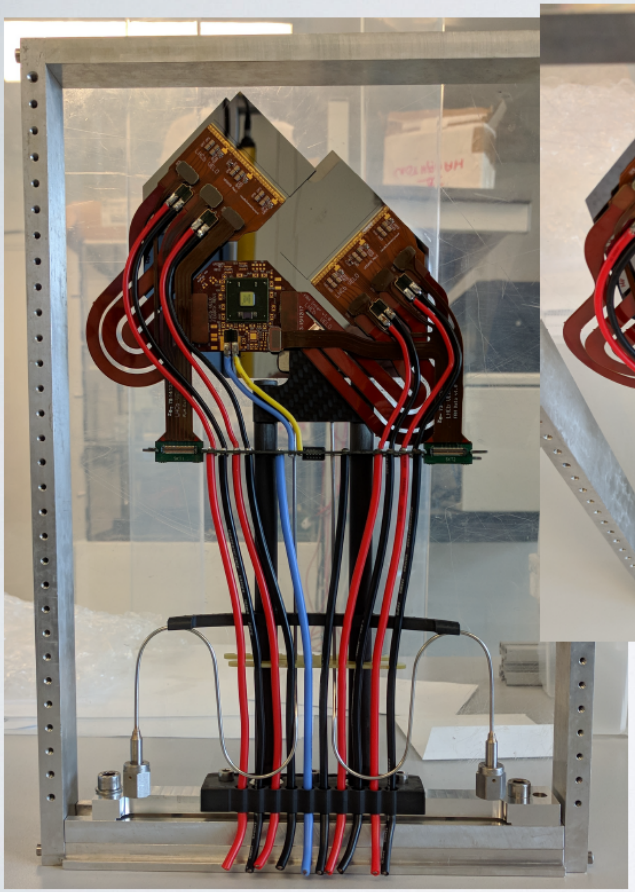
- Sensor is bump-bonded to 3 VeloPix ASICs
- Hamamatsu n-on-p 200 μm thickness
- Elongated pixels (137.5 μm) in the region between ASICs
- 450 μm wide guard ring
- DRIE-etched round corners (foil clearance)

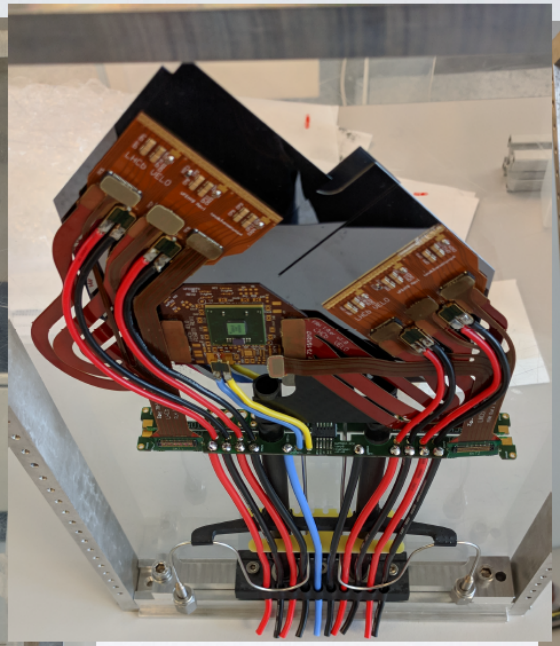
- Triggerless, binary readout (data-driven readout)
- Up to 800 Mhits/s/ASIC
- Highly non-uniform irradiation

For more info, see here.



First VELO module prototype



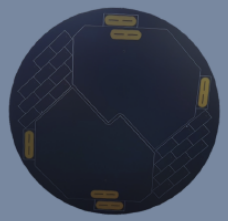


June 2018

Summary

- The new VELO will have to cope with higher radiation and data rates.
- New module design based on pixels sensors mounted on a Si micro-channel substrate.
- Aluminium RF-foil prototypes progressing well.
- Sensor tiles irradiated and extensively characterised in test-beams.
- First Module prototypes in June 2018.

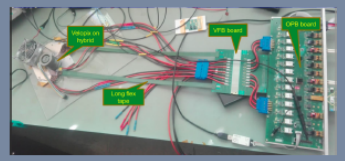
Sep 2017



Cooling EDR

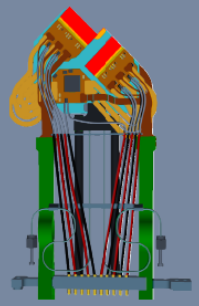
Apr 2018

RF foil PRR



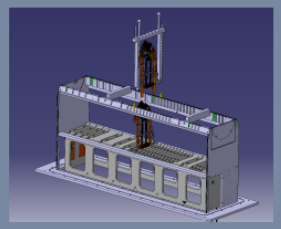
Electronics PRR

Jul 2018



Module PRR

Oct 2018



VELO integration PRR

- VELO fully mounted expected in September 2019.
- Install during LHC Long Shutdown 2 and take data in Run III

SUMMARY

Key points

- Building a detector is not easy
- Decide on your technology according to physics
  - Strips
  - Hybrid Pixels
  - CMOS (see mu3e talk)
    - HVCMOS is Liverpools #1 area of R&D in Si
- A lot of skill needed to execute