2nd Workshop on electromagnetic dipole moments of unstable particles
25-28 September 2022
Gargnano del Garda, Italy

LHCb hybrid pixels for Beauty, Bending and Beyond

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Gargnano del Garda
27th September 2022

Photo: SEM image of SnPb 55 μm pitch bumped Timepix wafer; courtesy of S. Vähänen, ADVACAM

Contents

- VELO Overview
  - Layout, Status
- ASIC
- Sensor
- Cooling
- Services

Try to focus on those aspects of the VELO which might be relevant for standalone detector

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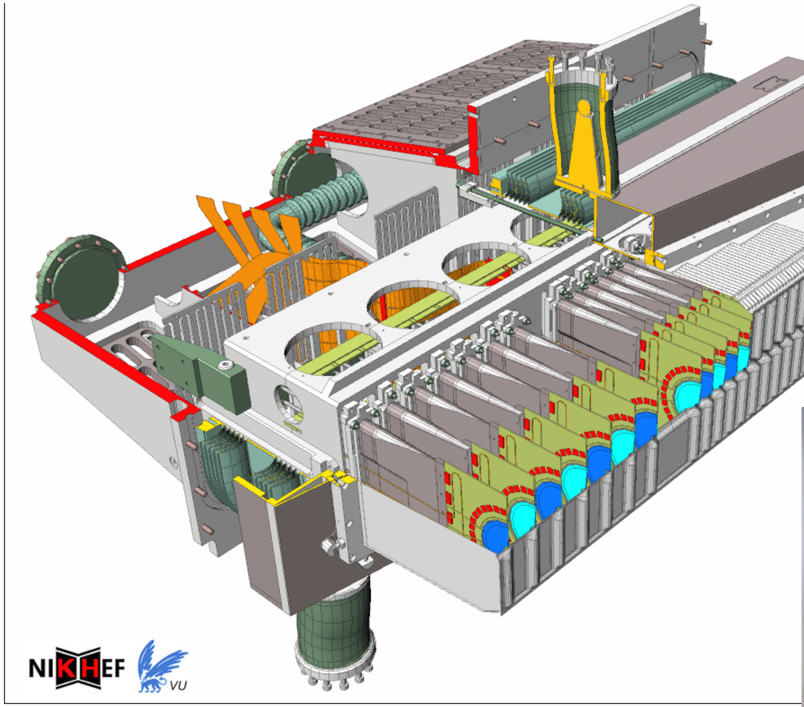
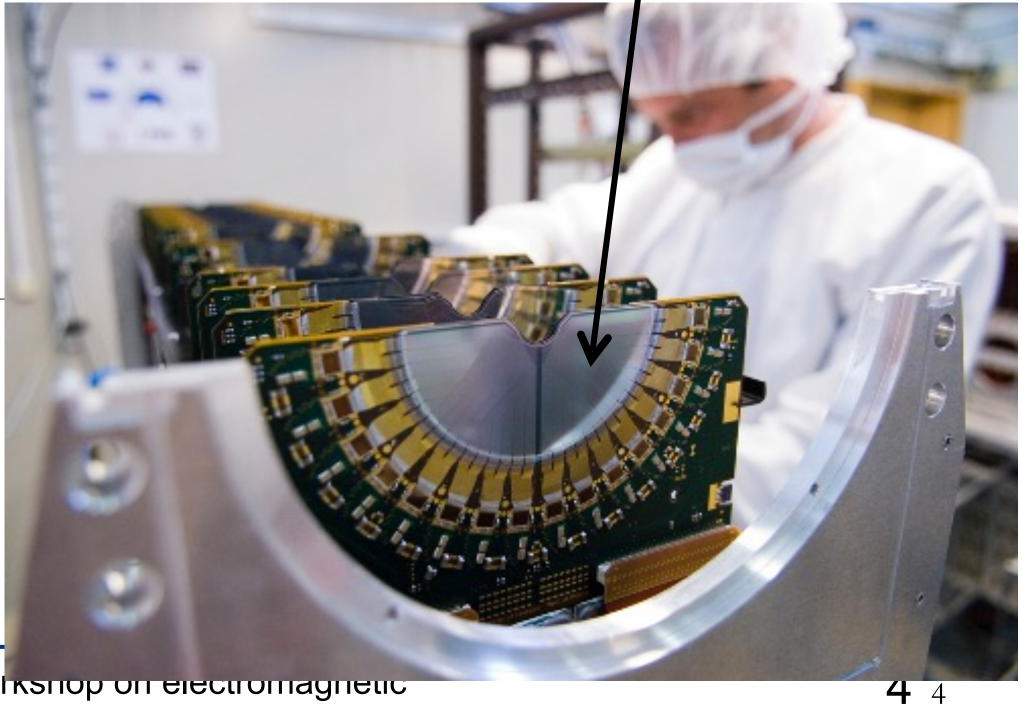
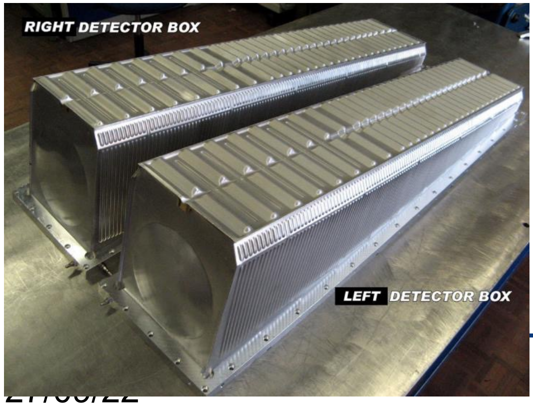
Legacy strip VELO

(as adapted by Massi for zap test)

- Silicon microstrip sensors



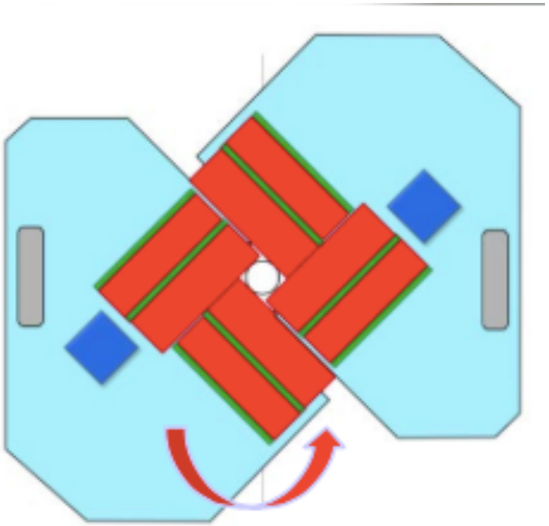


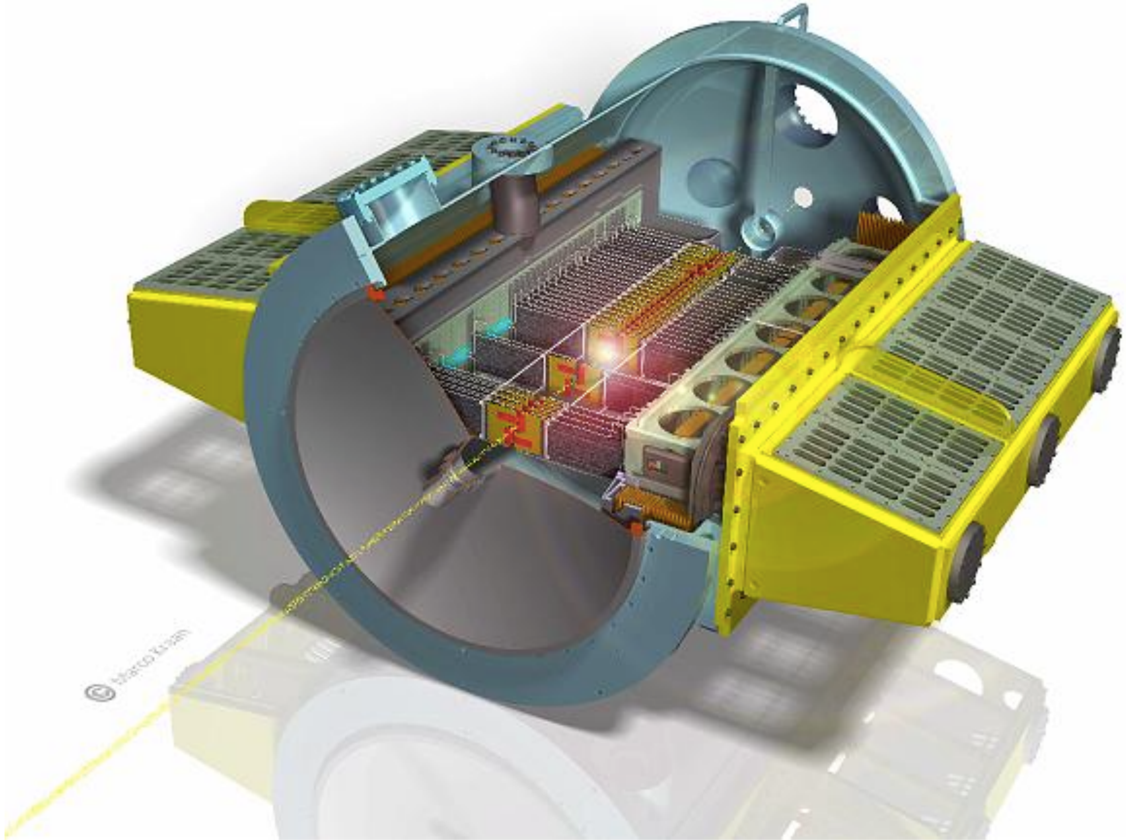


Upgraded Pixel VELO

Function of VELO remains: provide precise tracking and trigger on displaced vertices.
Conditions more challenging: increased occupancies, data rates and radiation damage.

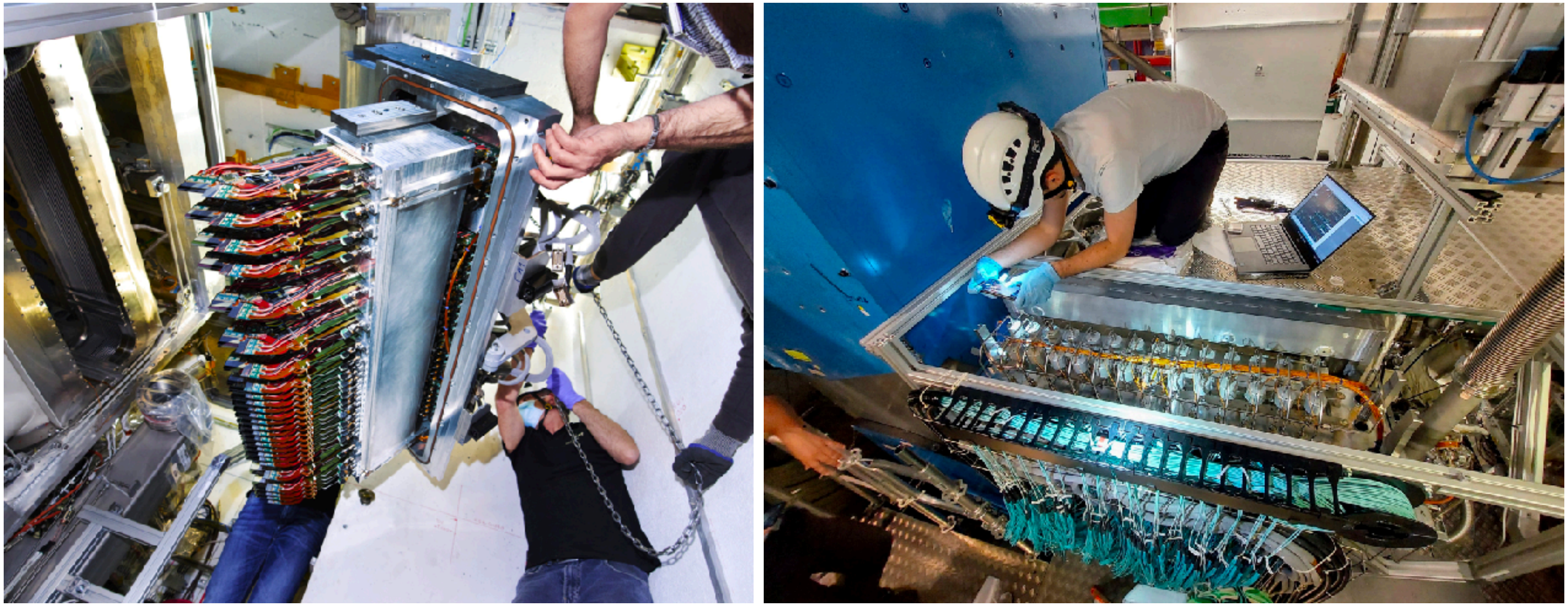
Choice made for new pixel detector equipped with two phase CO_2 microchannel cooling



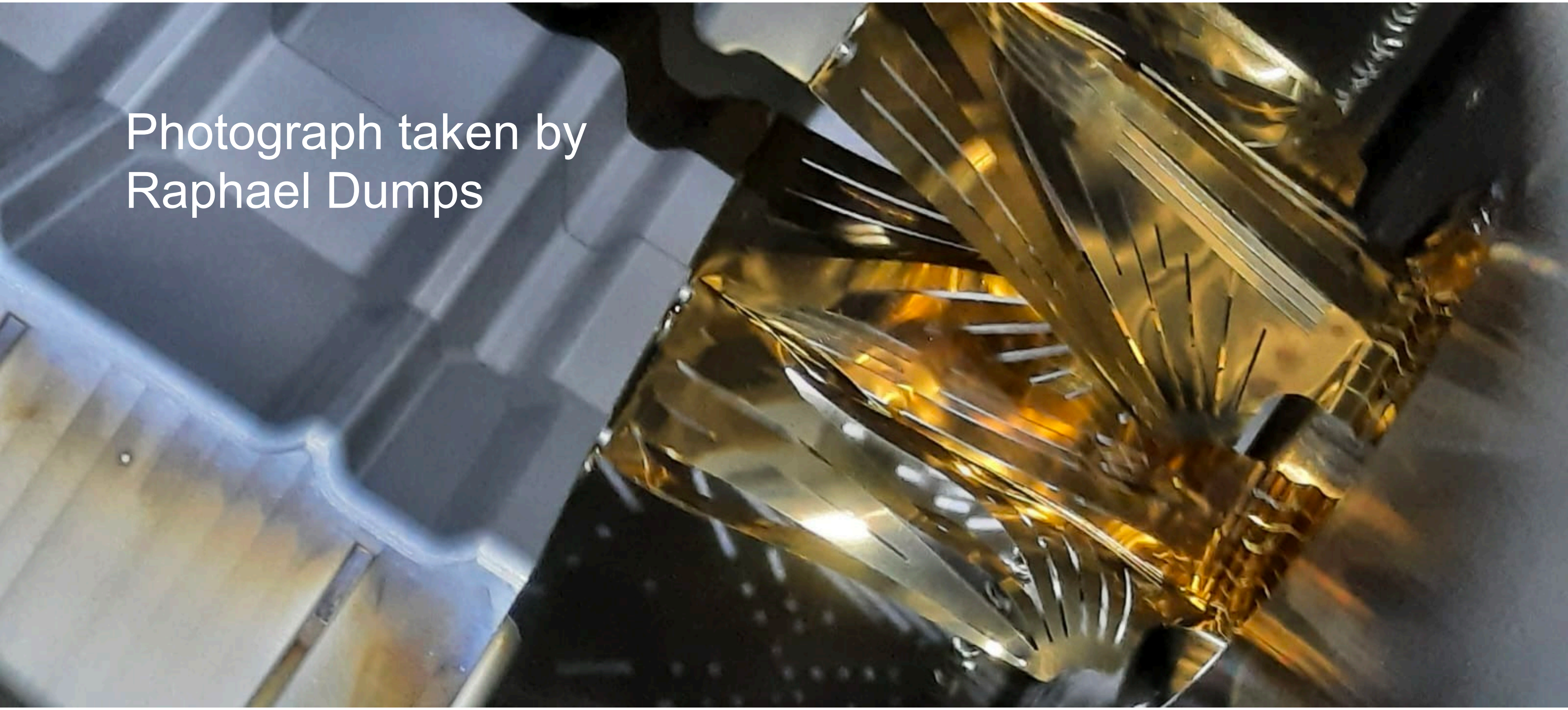


VELO Installation

At the end of May the second (and final) half of the VELO was installed into its vacuum tank and successfully connected to the cooling, powering and readout



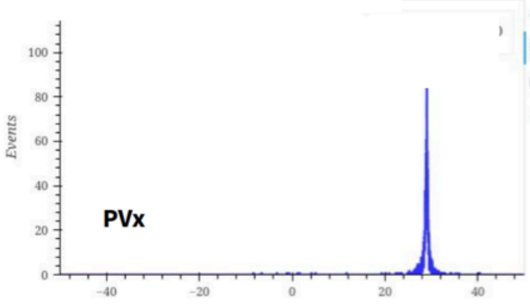
VELO downstream WFS

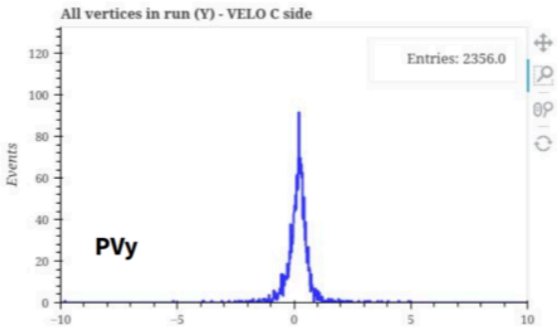


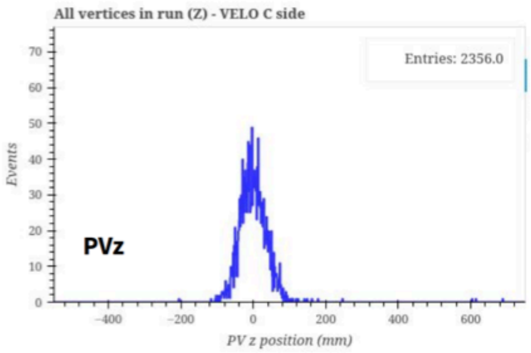
Photograph taken by Raphael Dumps

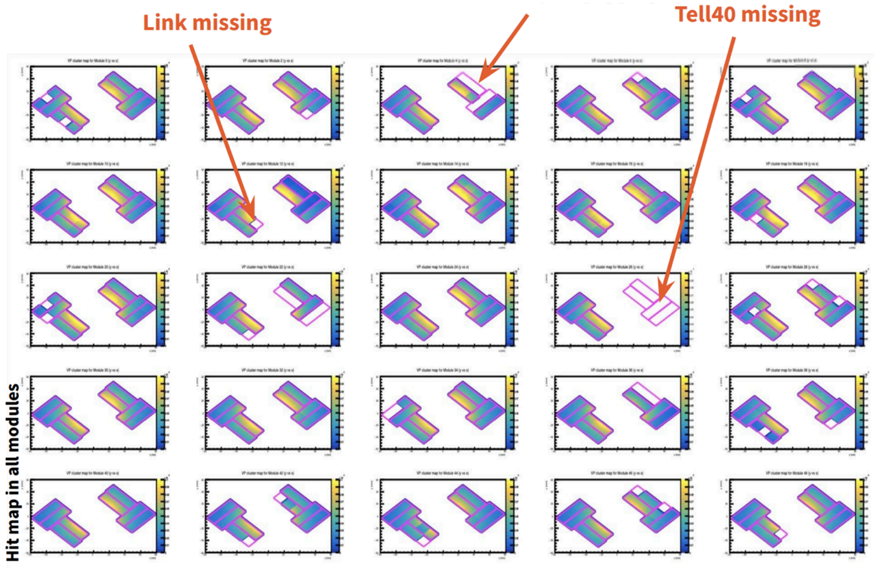
VELO Commissioning

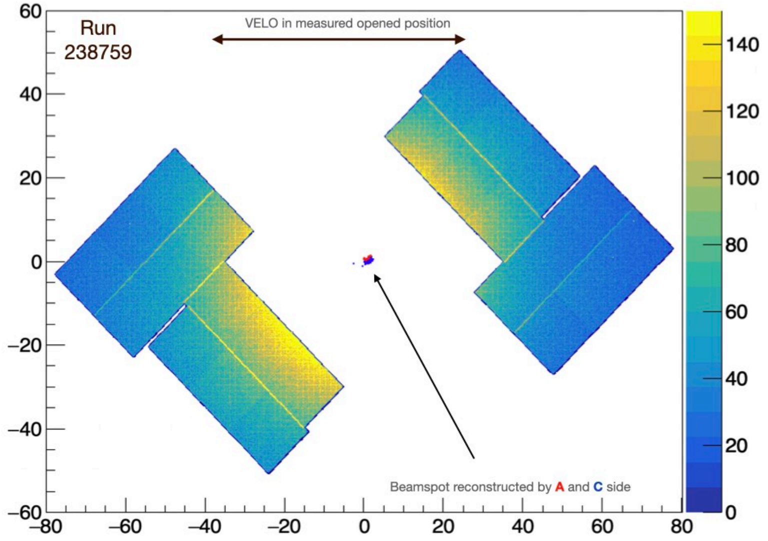
VELO is 98% up and running, and reconstructing tracks and vertices independently from the two halves.
Focus is currently on pixel calibrations and time alignment to bring efficiency up to 100%



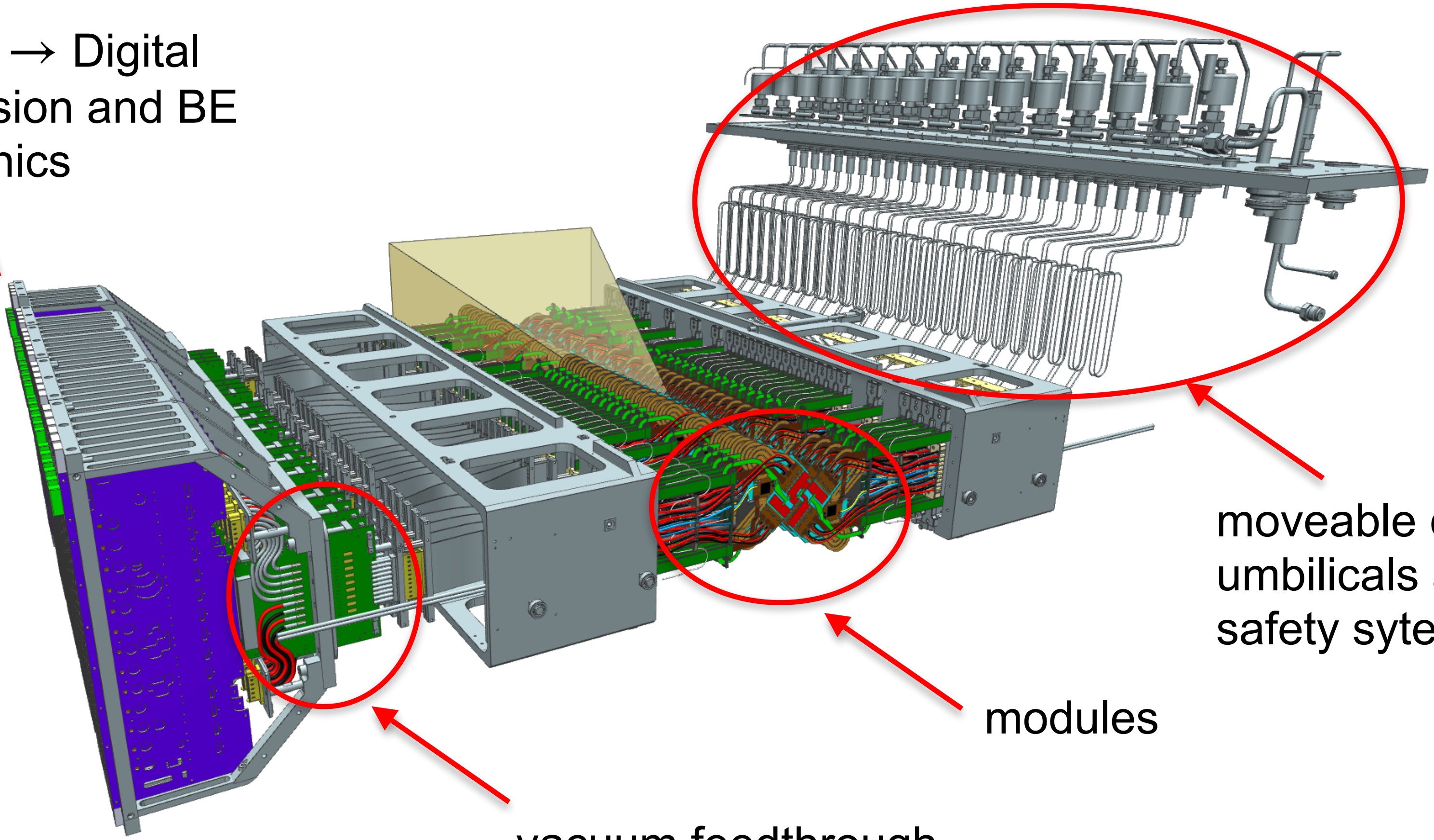








Anatomy of the VELO I



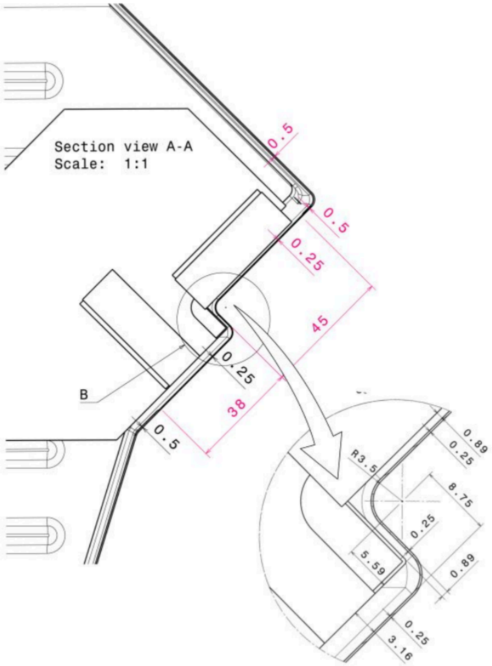
Optical → Digital conversion and BE electronics

moveable cooling umbilicals and safety sytem

modules

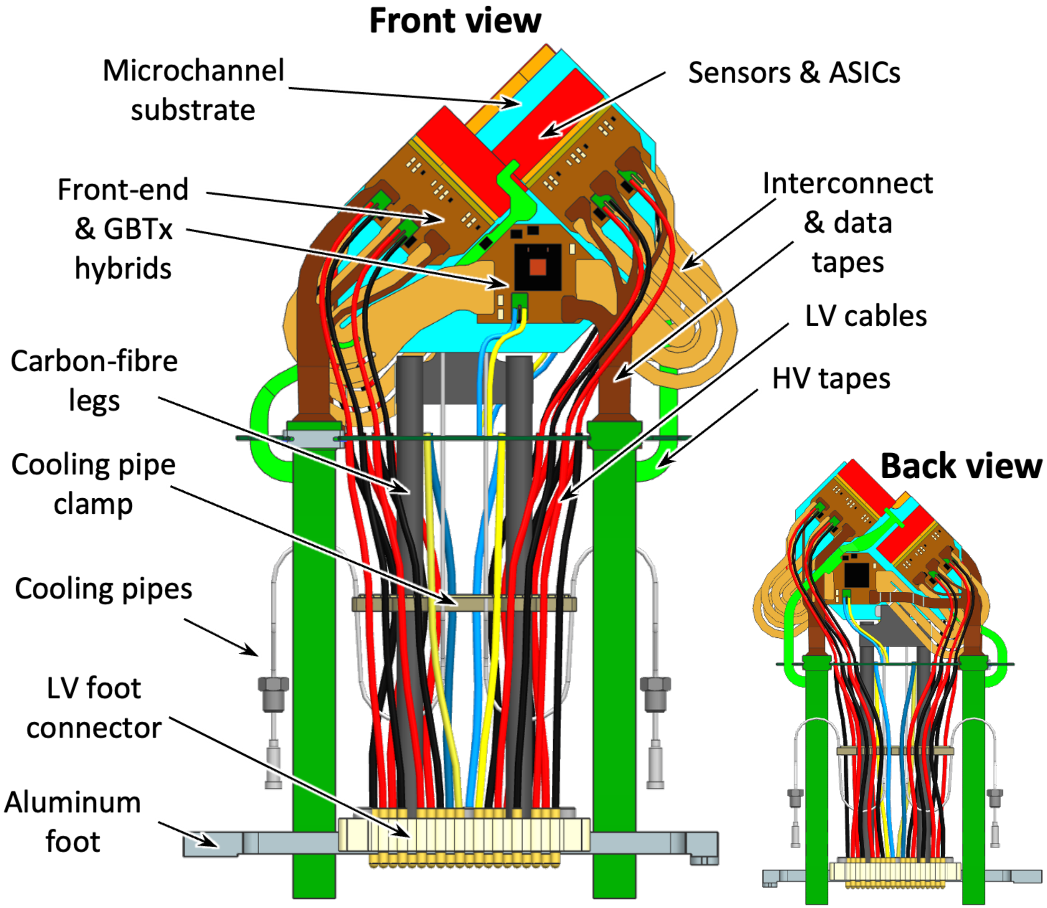
vacuum feedthrough

Anatomy of the VELO II

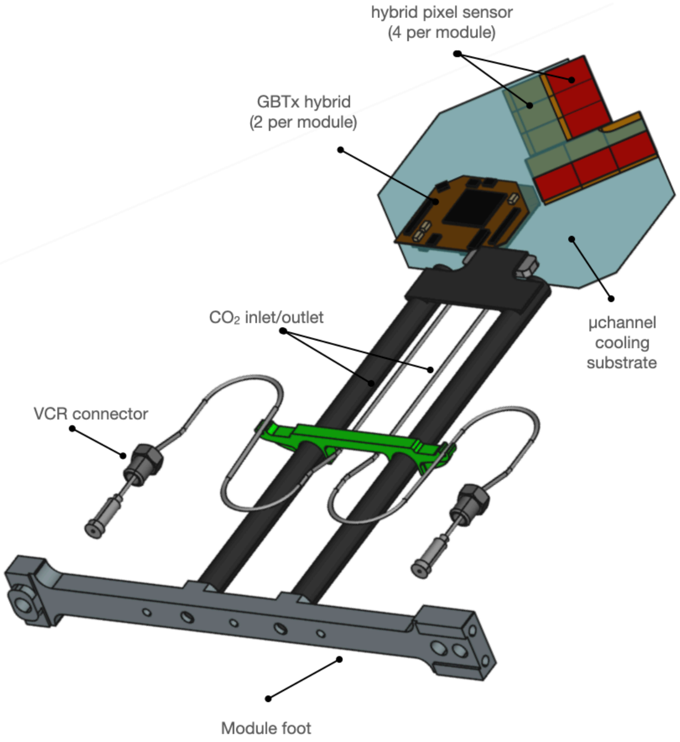


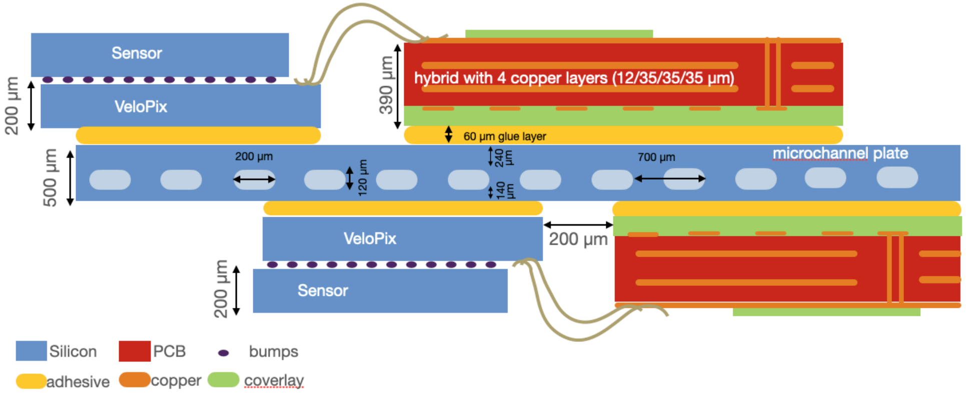
Old RF “foil” replaced by new RF boxes - milled from a solid block then chemically etched to 150 μm thin for beampipe region

Anatomy of the Module I



Anatomy of the Module II





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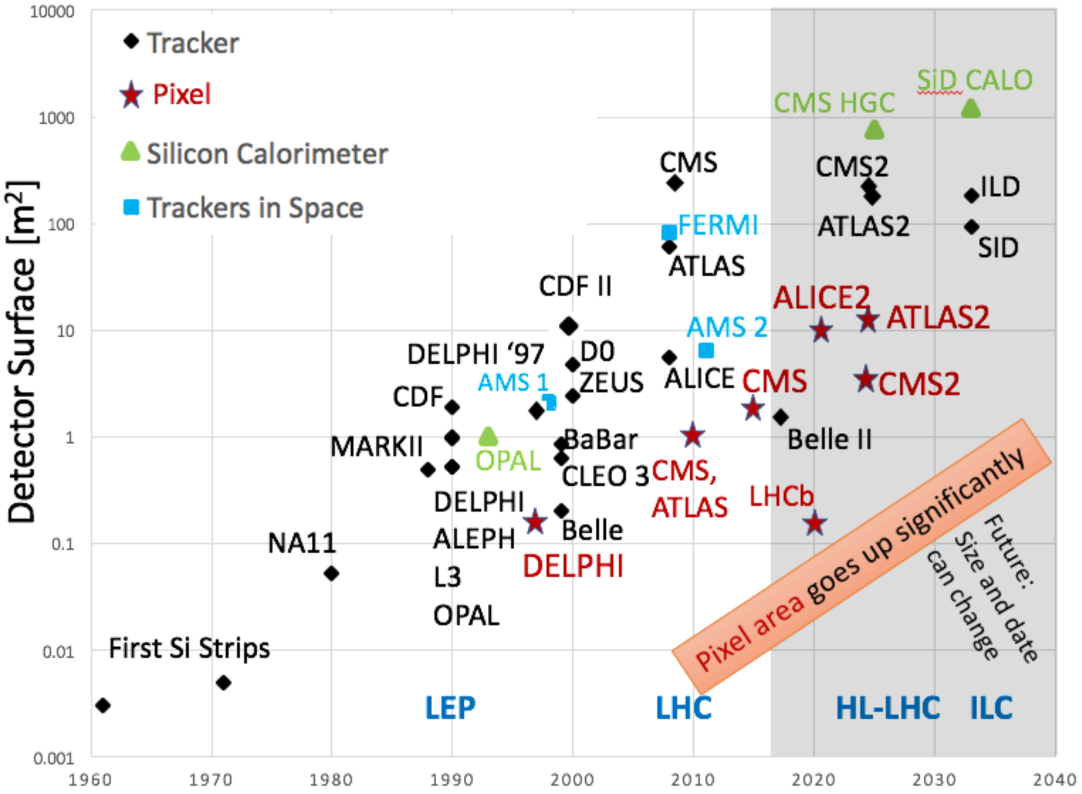
VELO in line with rise of hybrid pixels



Based on: Frank Hartmann, HSTD2017

In general global tracker sizes are saturating

However cell sizes and data rates are evolving significantly

Detector	Current	Upgrade
CMS strips	9.8M	42M + **172M**
CMS Pixels	127M	2GP
ATLAS strips	6.3M	60M
ATLAS pixels	92M	**5GP**
VELO	171k	41M
ALICE	12.5M	**12.5G**

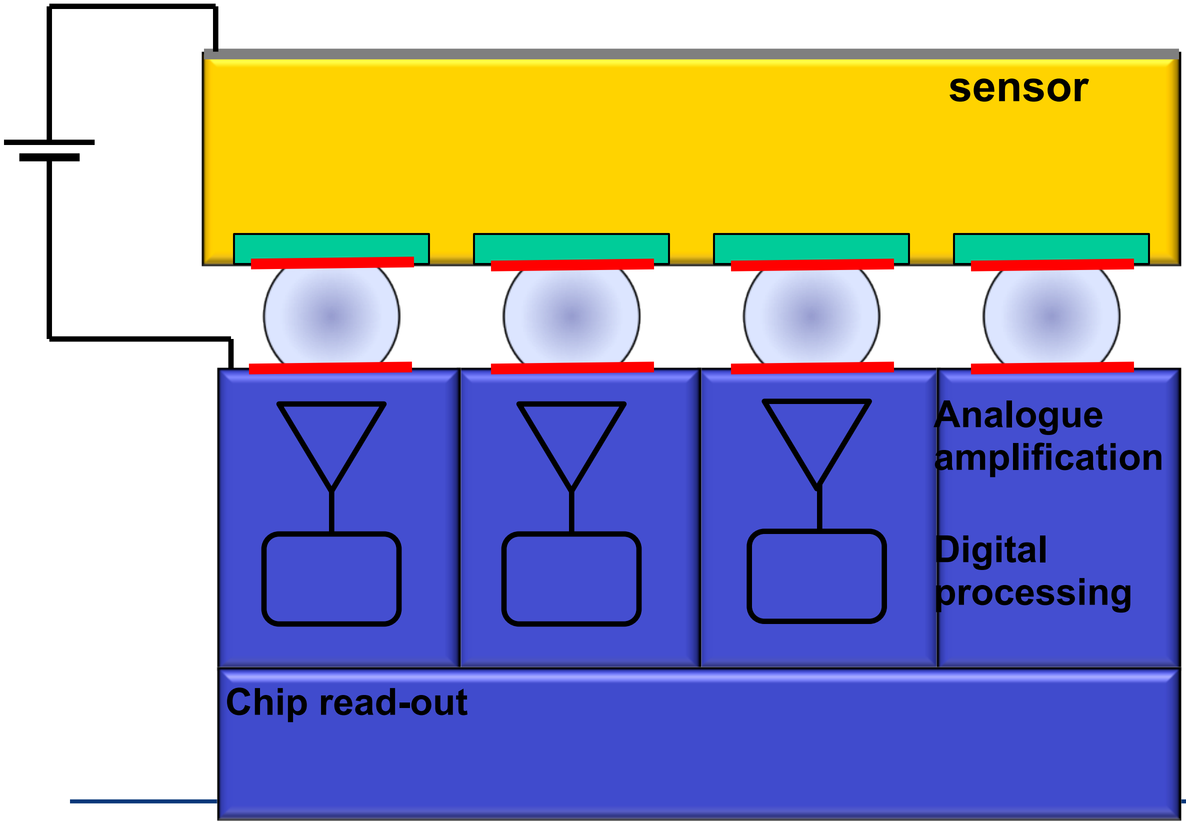
Cell granularity, the weapon against high-PU keeping occupancy at a reasonable level

Hybrid Pixels: Medipix/Timepix

Hybrid pixels used in tracking detectors, gaseous detector readouts, RICH, biomedical applications and photon science, space applications etc…

In the case of the VELO close integration with Medipix/Timepix family.

Pixels for Medical Imaging

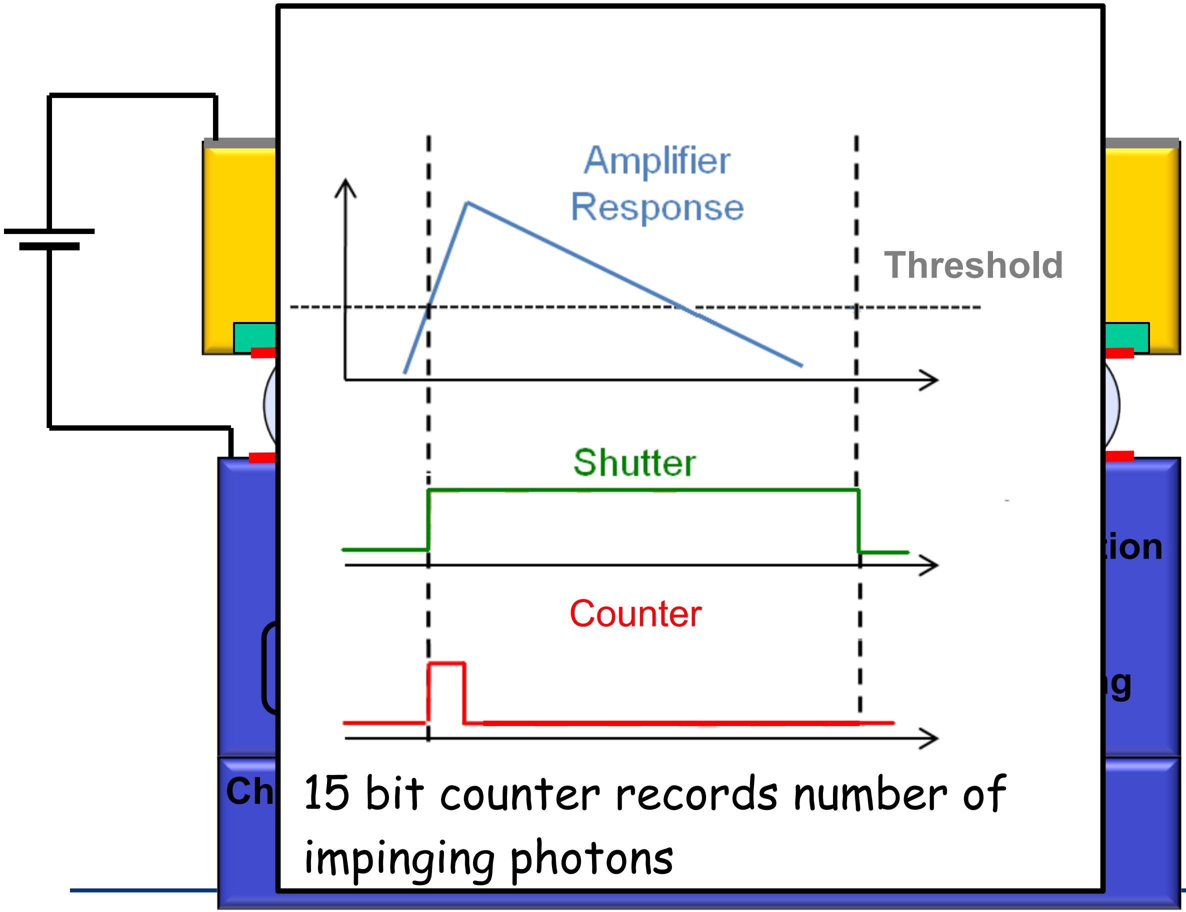


Idea: take advances in HEP and apply them to photon counting for medical physics

Intensity counter for photons, using individual pre-amp, comparator and counter per pixel

Operates in “camera” mode, reading out the entire pixel array when the shutter closes

Pixels for Medical Imaging



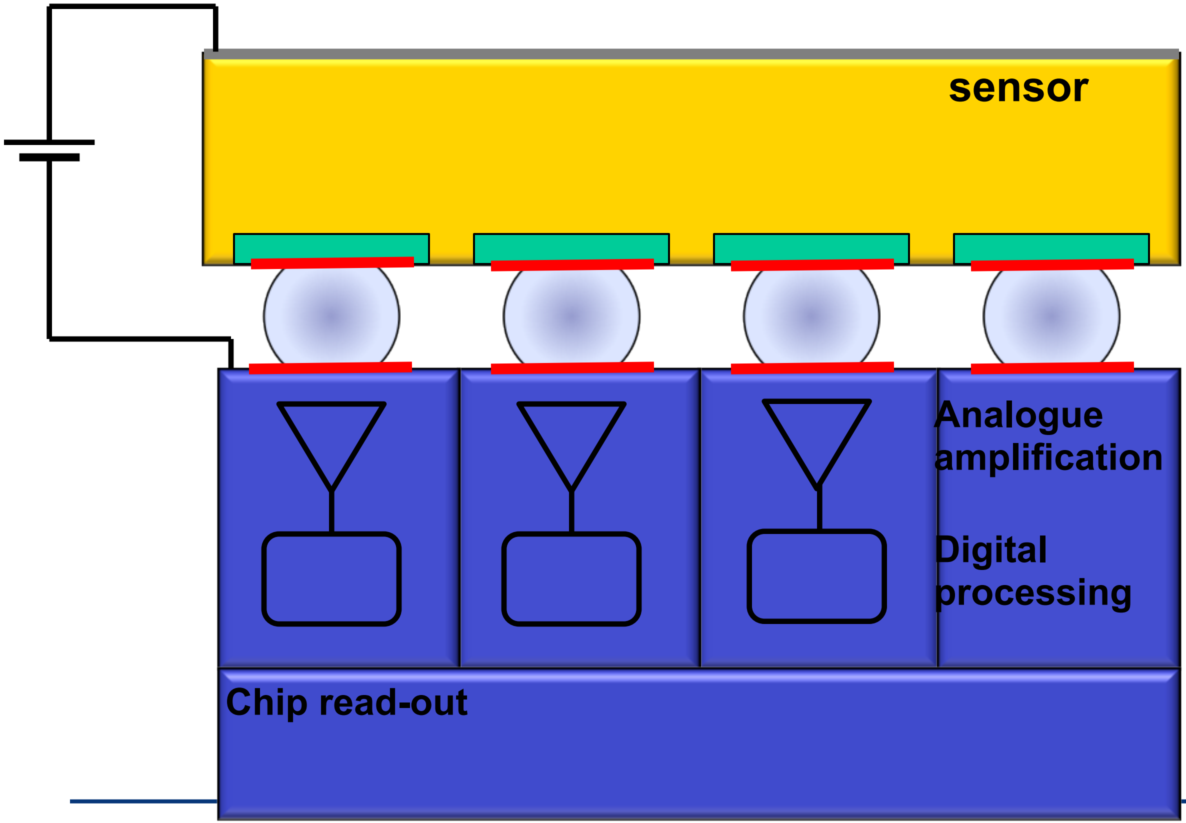
15 bit counter records number of impinging photons

Idea: take advances in HEP and apply them to photon counting for medical physics

Intensity counter for photons, using individual pre-amp, comparator and counter per pixel

Operates in “camera” mode, reading out the entire pixel array when the shutter closes

Pixels for Medical Imaging



Timepix design requested and funded by EUDET collaboration

Conventional Medipix2 counting mode remains.

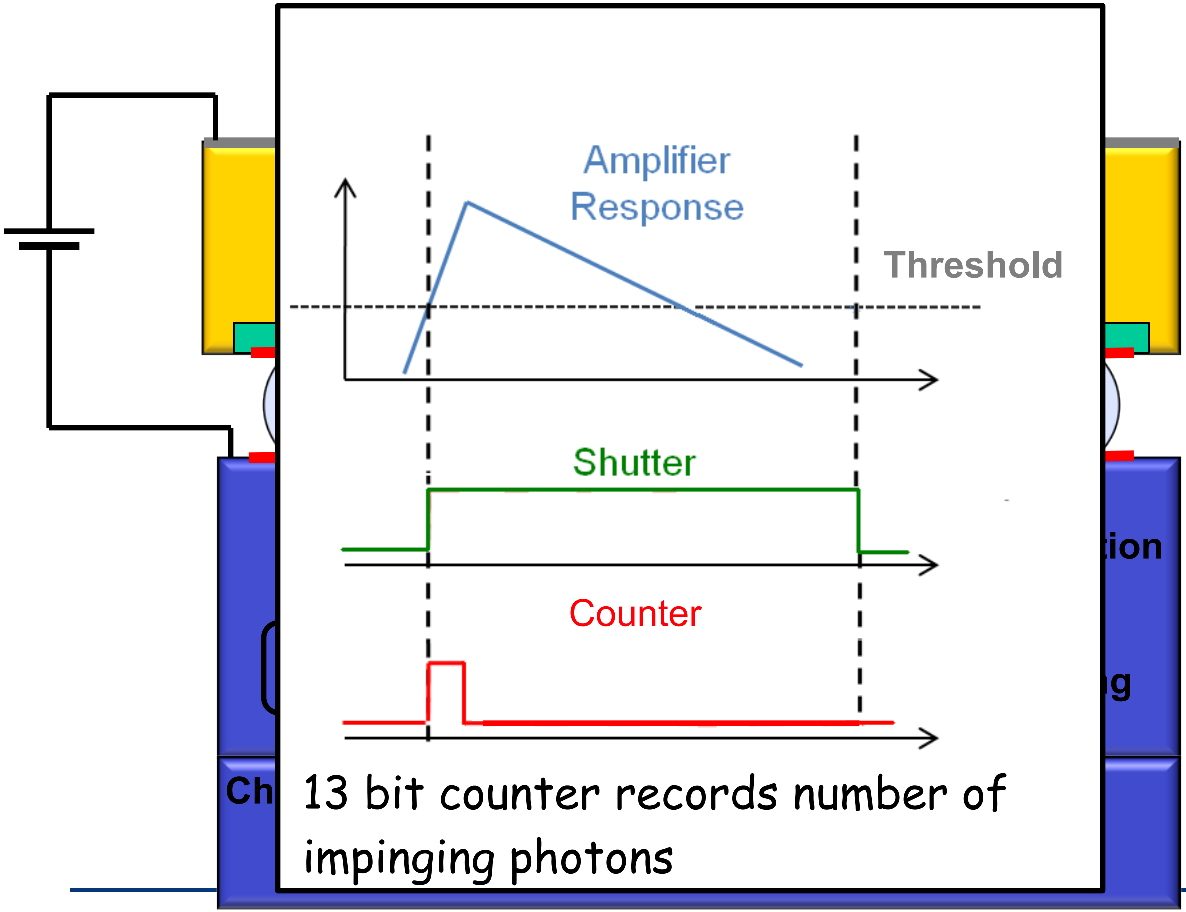
Addition of a clock up to 100MHz allows two new modes.

Time over Threshold

Time of Arrival

Pixels can be individually programmed into one of these three modes

Pixels for Medical Imaging



13 bit counter records number of impinging photons

Timepix design requested and funded by EUDET collaboration

Conventional Medipix2 counting mode remains.

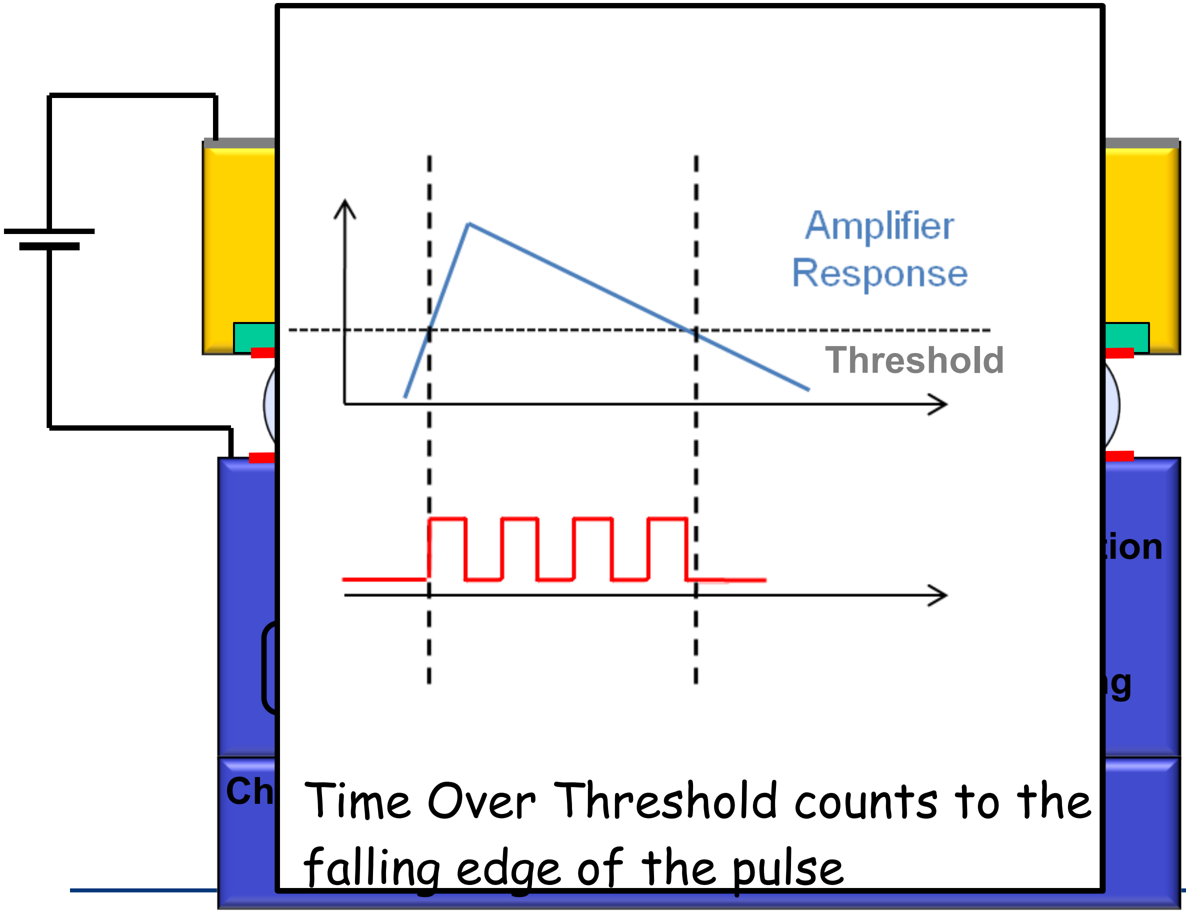
Addition of a clock up to 100MHz allows two new modes.

Time over Threshold

Time of Arrival

Pixels can be individually programmed into one of these three modes

Pixels for Medical Imaging



Time Over Threshold counts to the falling edge of the pulse

Timepix design requested and funded by EUDET collaboration

Conventional Medipix2 counting mode remains.

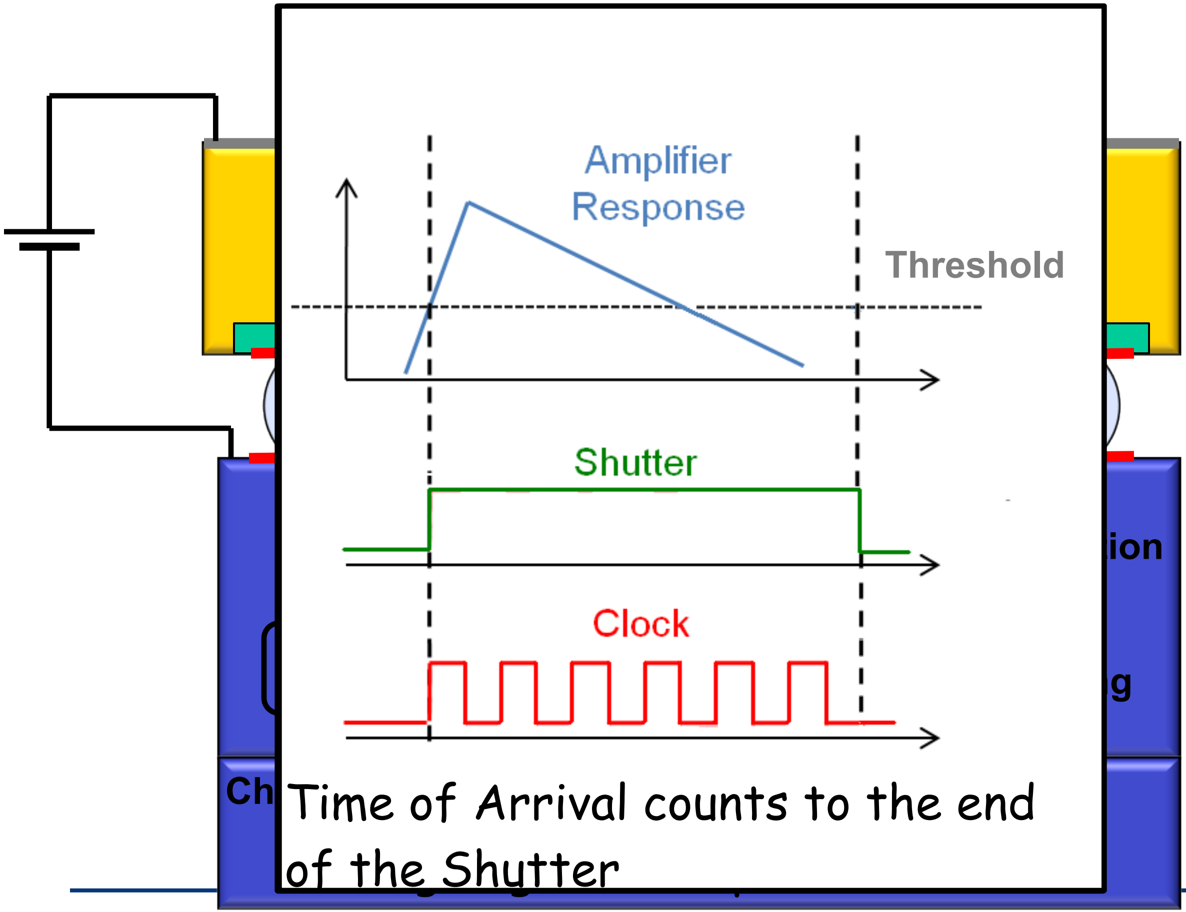
Addition of a clock up to 100MHz allows two new modes.

Time over Threshold

Time of Arrival

Pixels can be individually programmed into one of these three modes

Pixels for Medical Imaging



Time of Arrival counts to the end of the Shutter

Timepix design requested and funded by EUDET collaboration

Conventional Medipix2 counting mode remains.

Addition of a clock up to 100MHz allows two new modes.

Time over Threshold

Time of Arrival

Pixels can be individually programmed into one of these three modes

Low energy threshold (4 keV) enables imaging of very low contrast media, like flowers, with high resolutions

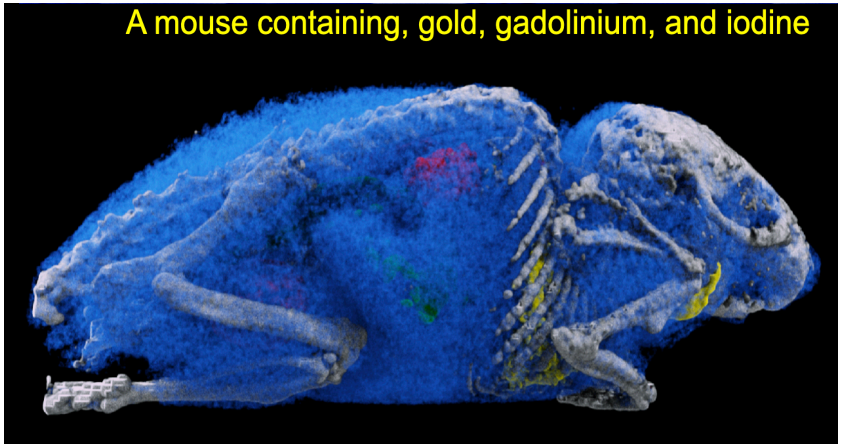
Medipix3: Convolvulus arvensis
3.1M pixels, 55 µm pixel pitch
Credits: Simon Procz,, Ph.D. Thesis,
University of Freiburg

Spectral Imaging with MARS

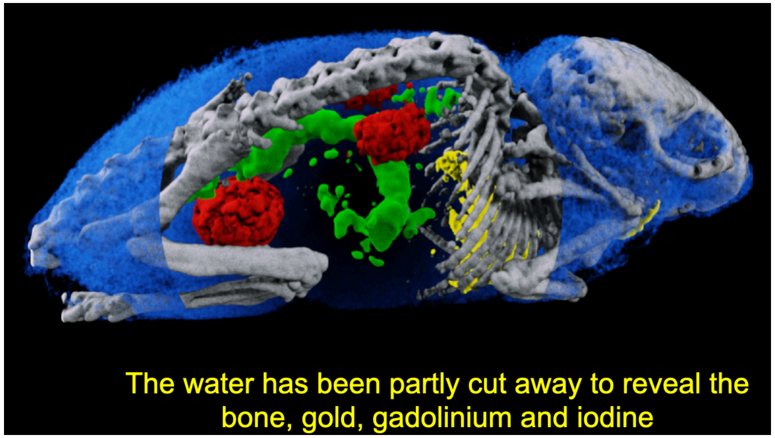
Spectral imaging allows different materials to be identified and quantified

Separate map (data channel) made for each material
Each map gives the partial density (g/cm3) for the material
Each material assigned a colour for easy visualisation

A phantom containing Au, Gd, Iodine, Lipid, Water and hydroxyapatite



A mouse containing, gold, gadolinium, and iodine



The water has been partly cut away to reveal the bone, gold, gadolinium and iodine

Timepix Specs - particle tracking!

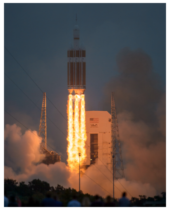
Timepix Specs

CMOS node	**250nm**
Pixel Array	**256 x 256**
Pixel pitch	**55μm**
Charge collection	**e^-, h^+**
Pixel functionality	**PC (Particle Counting), TOT (Energy) or TOA (Arrival time)**
Preamp Gain	**~16.5mV/ke$^-$**
ENC	**~100e$^-$**
FE Linearity	**Up to 50ke$^-$**
TOT linearity (resolution)	**Up to 200ke$^-$ (<5%)**
TOA resolution	**Up to 10ns (@ 100 MHz)**
Time-walk	**<50ns**
Minimum detectable charge	**~700e$^-$ → 2.5 KeV (Si Sensor)**
Counter Depth/Overflow	**14-bits(11810)/Yes**
Max Analog power (2.2V)	**6.5μW/pix 190mA/chip**
Static Digital Power (2.2V)	**~500mW@100MHz/chip**
Readout (@ 100 MHz)	**Serial readout → 9.17 ms** **32-bit Parallel readout → 287 μs**

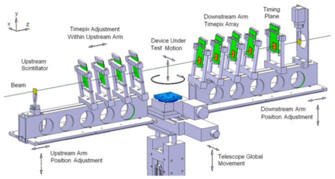
3 side buttable floor plan
> 36M Transistors
Medipix / Timepix / Medipix3
photon counting/ add time / energy thresholds


miniaturised readout
IEAP/CTU, Prague

Many applications..



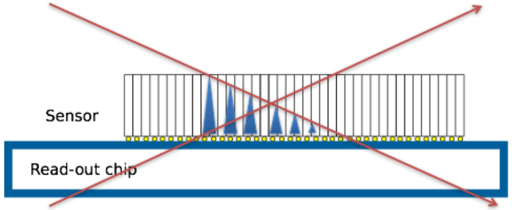
including the Timepix particle tracking telescope



Timepix3 Specs

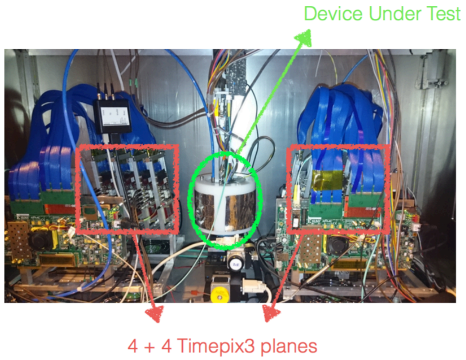
Timepix3 Specs

CMOS node	**130nm**
Pixel Array	**256 x 256**
Pixel pitch	**55μm**
Charge collection	**e^-, h^+**
Pixel functionality	**TOT (Energy) and TOA (Arrival time)**
Preamp Gain	**~47mV/ke$^-$**
ENC	**~60e$^-$**
FE Linearity	**Up to 12ke$^-$**
TOT linearity (resolution)	**Up to 200ke$^-$ (<5%)**
TOA resolution*	**Up to 1.6ns**
Time-walk	**<20ns**
Minimum detectable charge	**~500e$^-$ → 2 KeV (Si Sensor)**
Max Analog power (1.5V)	**500 mA/chip**
Digital Power (1.5V)	**~400mA data driven**
Maximum hit rate	**80Mhits/sec (in data driven)**
Readout	**Data driven (44-bits/hit @ 5Gbps)**



tracking in single Si layer conceivable

X ray materials analysis, gamma camera, compton camera, electron microscopy, neutron and photon imaging… and particle tracking for the Timepix3 telescope



VeloPix for LHCb Upgrade I

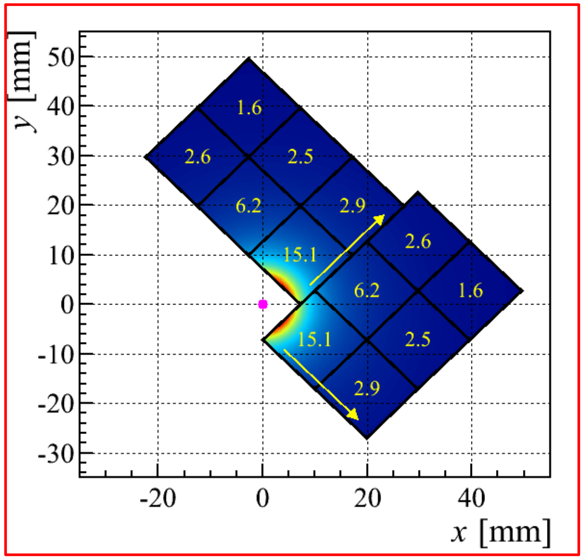
ASIC challenges: data rate & radiation hardness

- Sensor and ASIC exposed to high, non-homogeneous, radiation fluence
  - Only part of the pixel matrix gets the full dose of ~ 370 Mrad
  - TID at periphery of chip is factor 10 lower

- For data rates calc. we assume collisions in every LHCb bunch crossing
  - in reality only 2/3 of bunches collide
  - would require a lot of memory to level out
  - → assume peak rates for ASIC design
- Data flow simulations using physics Monte Carlo data

- No trigger, all data sent off chip
- Hottest ASIC gives ~20 Gbps

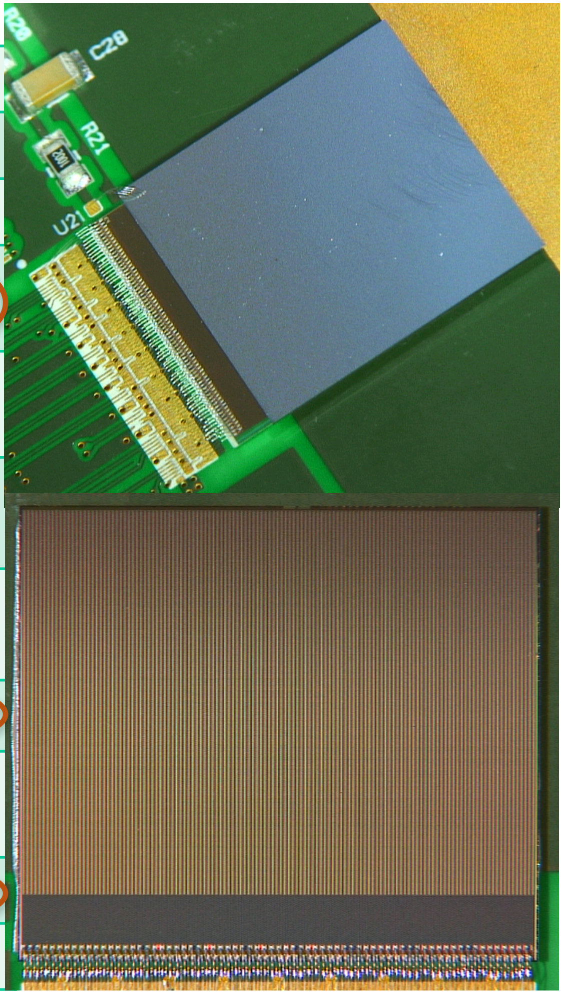
- ASIC design starting point: Timepix3



VeloPix for LHCb Upgrade I

Derived from Timepix3 and dedicated to LHCb.

	Timepix3 (2013)	VeloPix (2016)
Pixel arrangement	256 x 256	
Pixel size	55 x 55 μm^2	
Peak hit rate	80 Mhits/s/ASIC	800 Mhits/s/ASIC 50 khits/s/pixel
Readout type	Continuous, trigger-less, TOT	Continuous, trigger-less, binary
Timing resolution/ range	1.5625 ns, 18 bits	25 ns, 9 bits
Total Power consumption	<1.5 W	< 3 W
Radiation hardness		400 Mrad, SEU tolerant
Sensor type	Various, e- and h+ collection	Planar silicon, e- collection
Max. data rate	5.12 Gbps	20.48 Gbps
Technology	IBM 130 nm CMOS	TSMC 130 nm CMOS



VeloPix

Design started 2013
Engineering runs 2016/2017

Double column:

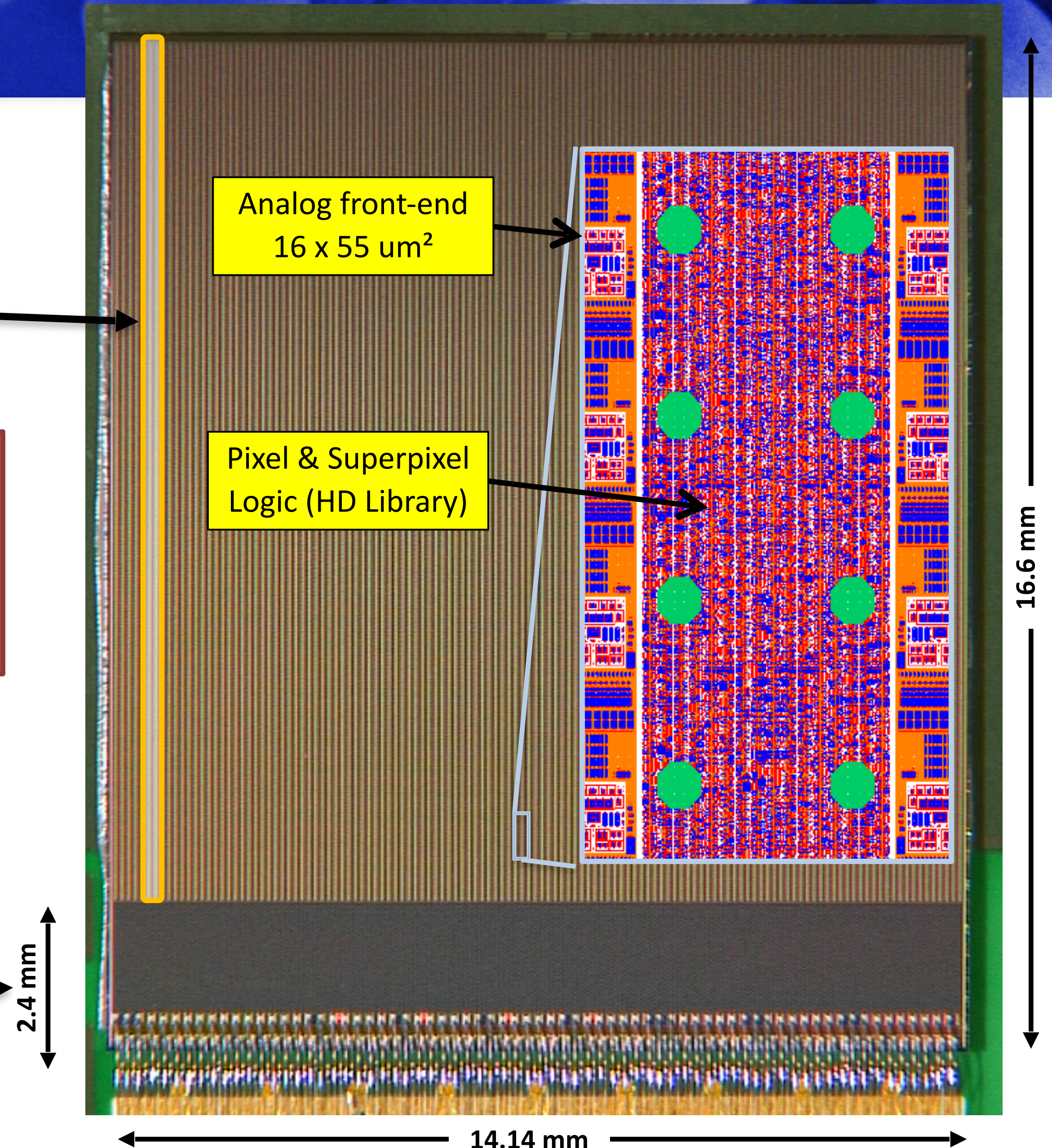
- 512 pixels
- 64 super pixels

Full matrix:

- 128 Double columns
- ~190 Mtransistors
- 14.8nF digital decoupling (thick gate)

Active Periphery:

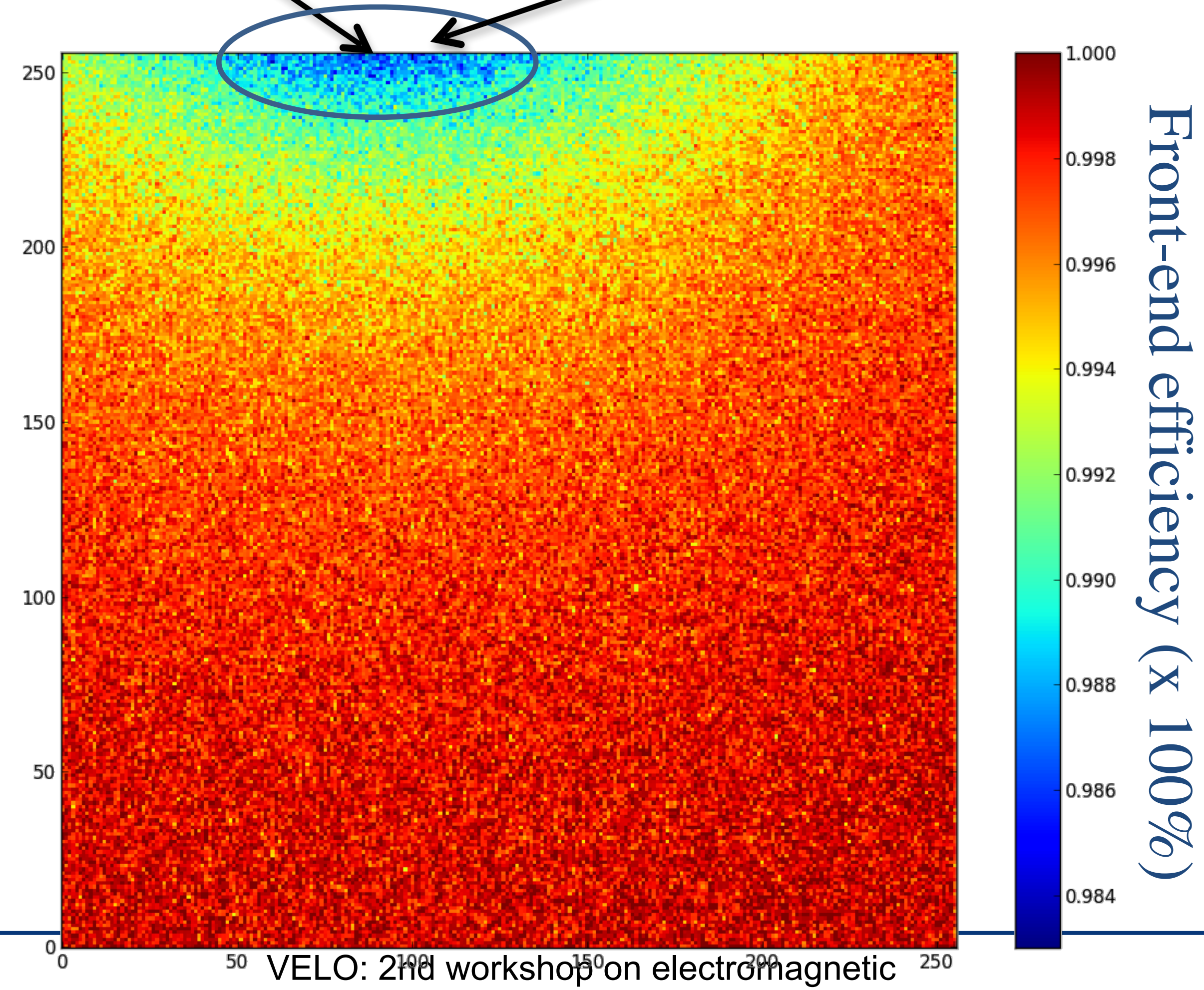
- 40, 80, 160 and 320 TMR clocks
- HVT TSMC (tcb013ghphvt library)
- 4nF digital decoupling (thin gate)



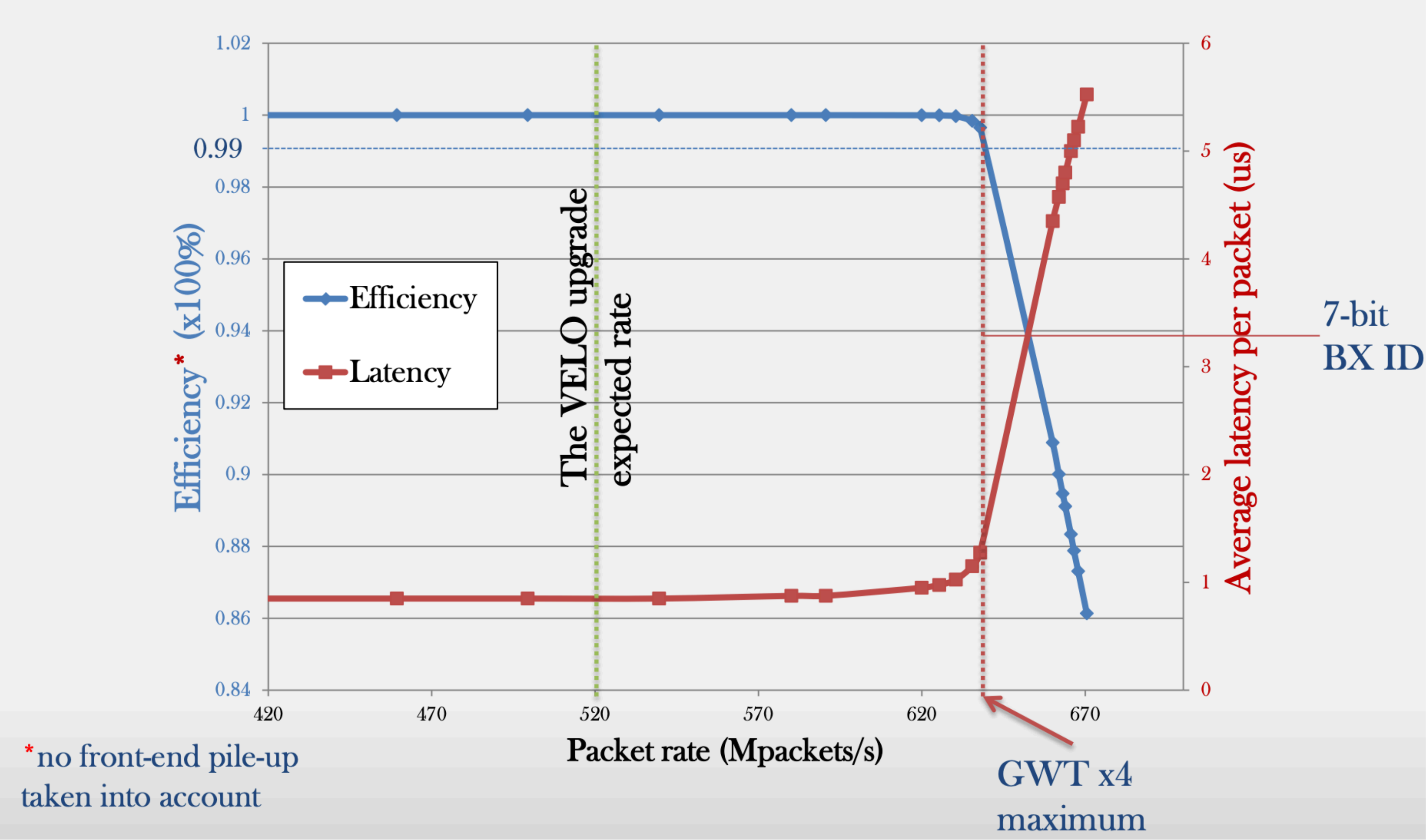
Analog Front End Pileup (simulated)

Up to 1.6% losses

Rates up to 50 kHz per pixel



Data Transfer Efficiency (simulated)



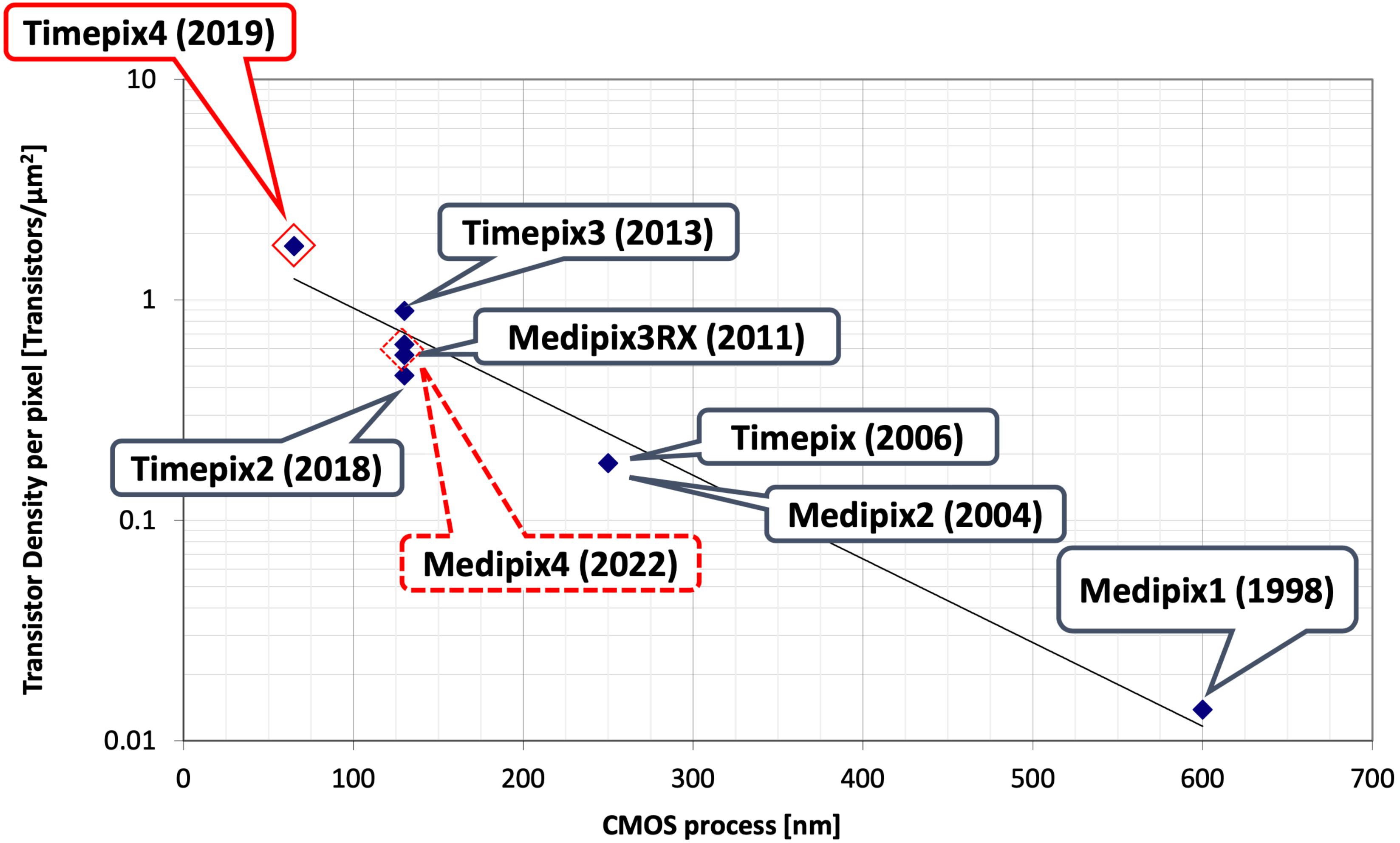
*no front-end pile-up taken into account

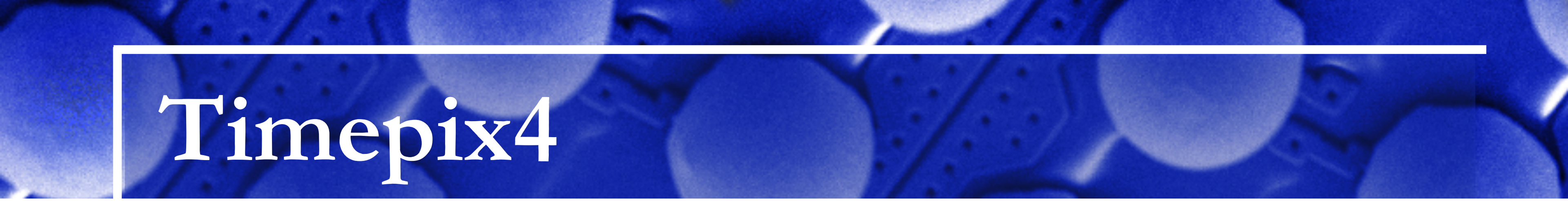
VELO pix lab performance (ECS)

- ✓ Measured power consumption (@nominal settings):
  - ✓ Analog supply < 480 mW
  - ✓ Digital: Periphery < 380mW, matrix ~ 300 mW at high rate (simulated)
  - ✓ Total= ~1.5W @High rate

Pixel gain	~24.6 mV/Ke$^-$
Pixel to pixel gain variation	~3.3%
Pixel ENC	62.9 e$^-$
Pixel to pixel threshold mismatch	410 e$^-$rms
Pixel to pixel threshold mismatch calibrated (Threq)	40.3 e$^-$rms
Expected minimum threshold	> 450 e-

Timepix4


Timepix4 (2019)
Timepix3 (2013)
Medipix3RX (2011)
Timepix2 (2018)
Medipix4 (2022)
Timepix (2006)
Medipix2 (2004)
Medipix1 (1998)
Transistor Density per pixel [Transistors/µm²]
10
1
0.1
0.01
0
100
200
300
400
500
600
700
CMOS process [nm]

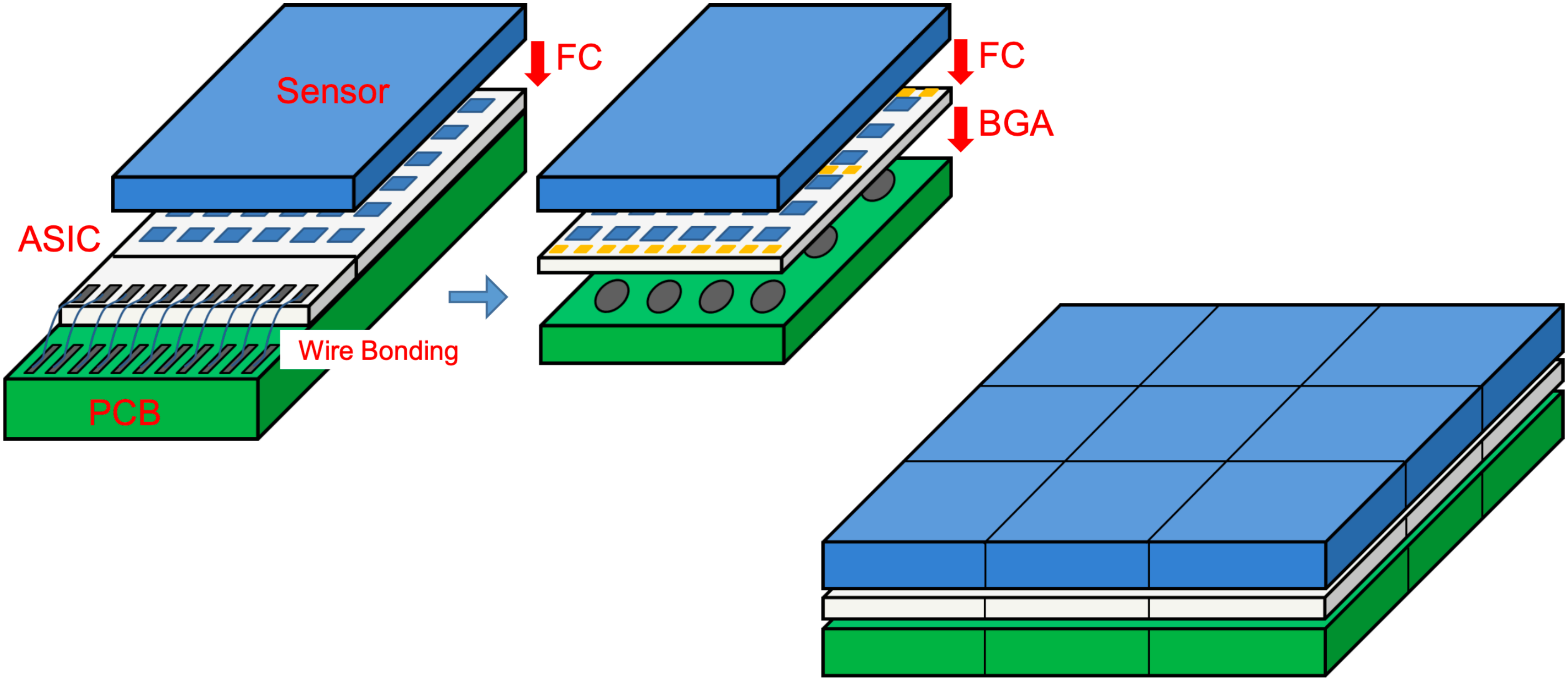


Timepix4

Timepix4: A 4-side tillable large single threshold particle detector chip with improved energy and time resolution and with high-rate imaging capabilities

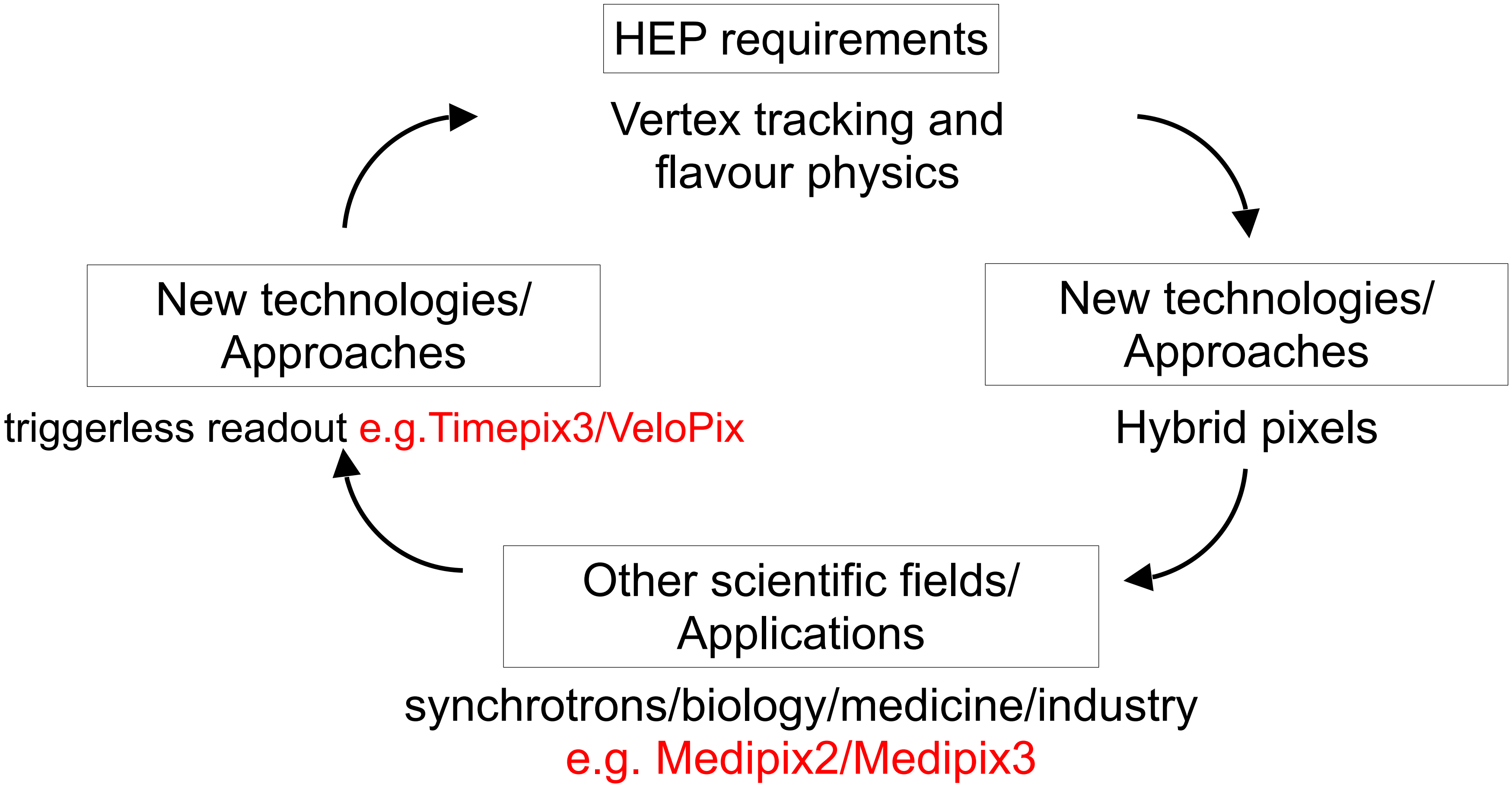
			Timepix3 (2013)	**Timepix4 (2019)**	
Technology			130nm – 8 metal	65nm – 10 metal	
Pixel Size			55 x 55 µm	55 x 55 µm	
Pixel arrangement			3-side buttable 256 x 256	4-side buttable 512 x 448	**3.5x**
Sensitive area			1.98 cm^2	6.94 cm^2	
Readout Modes	Data driven (Tracking)	Mode	TOT and TOA		
		Event Packet	48-bit	64-bit	**33%**
		Max rate	0.43×10^6 hits/mm^2/s	**3.58×10^6 hits/mm^2/s**	**8x**
		Max Pix rate	1.3 KHz/pixel	**10.8 KHz/pixel**	
	Frame based (Imaging)	Mode	PC (10-bit) and iTOT (14-bit)	CRW: PC (8 or 16-bit)	
		Frame	Zero-suppressed (with pixel addr)	Full Frame (without pixel addr)	
		Max count rate	~0.82 x 10^9 hits/mm^2/s	~5 x 10^9 hits/mm^2/s	**6x**
TOT energy resolution			< 2KeV	**< 1Kev**	**2x**
Time resolution			1.56ns	**195.3125ps**	**8x**
Readout bandwidth			≤5.12Gb (8x SLVS@640 Mbps)	≤163.84 Gbps (16x @10.24 Gbps)	**32x**
Target global minimum threshold			<500 e^-	<500 e^-	

Timepix4



- Target to build **large area detectors** by combining smaller modules
- The through-silicon vias (TSVs) is the key technology for this paradigm shift

Timepix / HEP cycle of innovation



HEP requirements

Vertex tracking and flavour physics

New technologies/ Approaches

Hybrid pixels

Other scientific fields/ Applications

synchrotrons/biology/medicine/industry
e.g. Medipix2/Medipix3

New technologies/ Approaches

triggerless readout e.g.Timepix3/VeloPix

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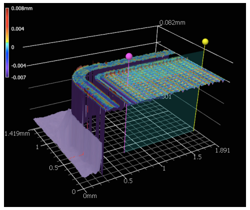
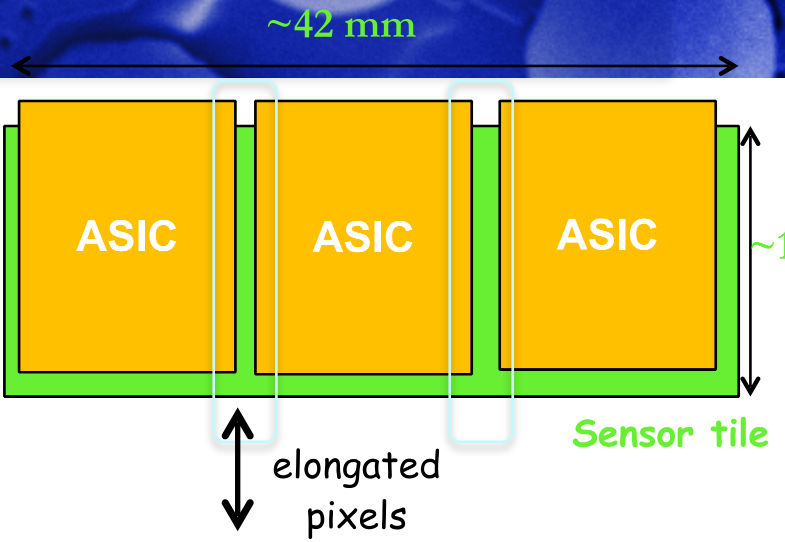
Sensors

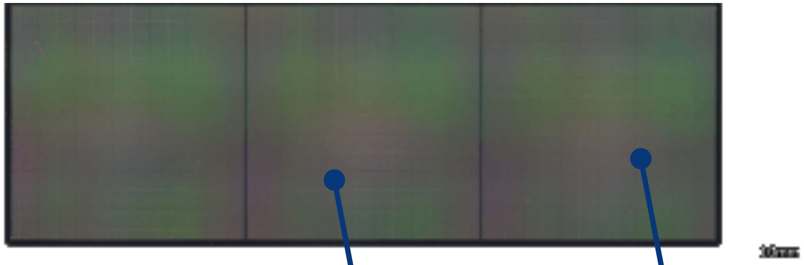
Triple sensor

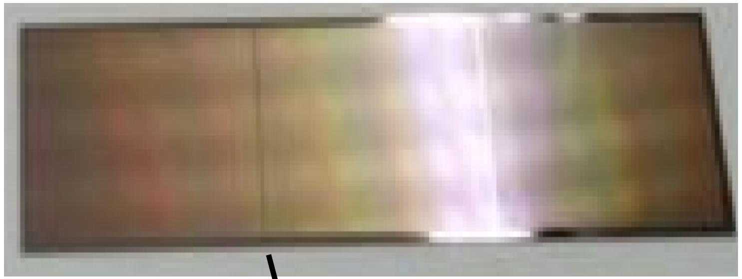
- 55 µm x 55 µm pixels
- n-in-p

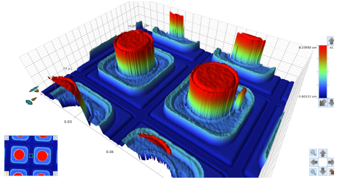


Sensor Thickness
200 µm

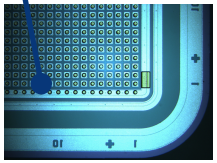




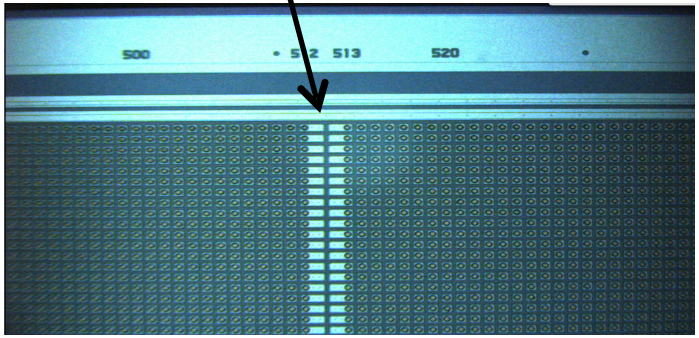




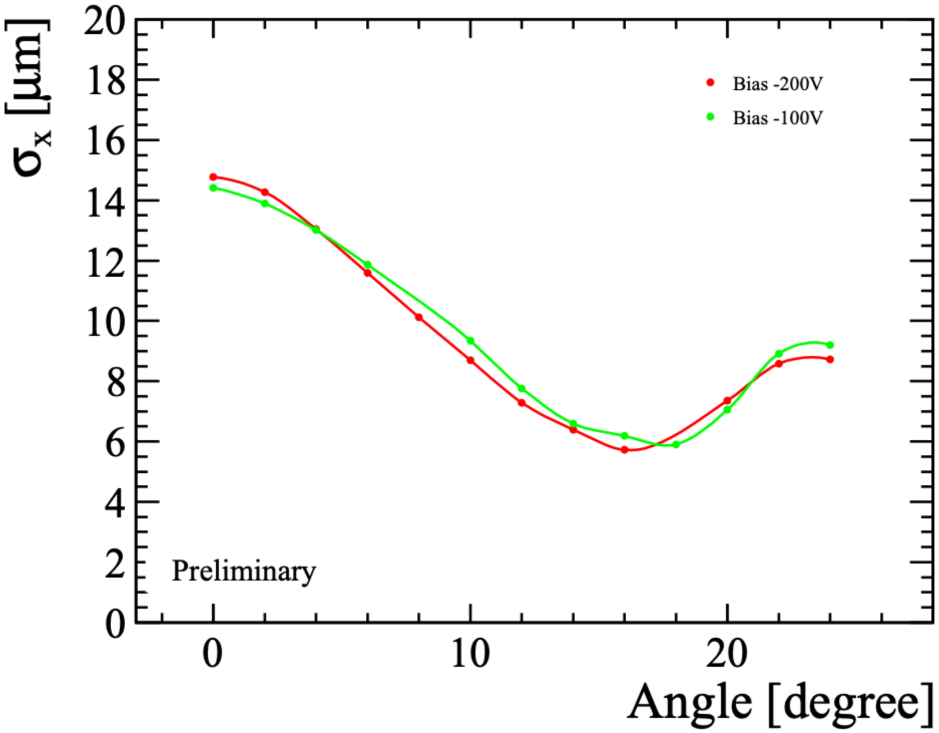
sensor UBM pads



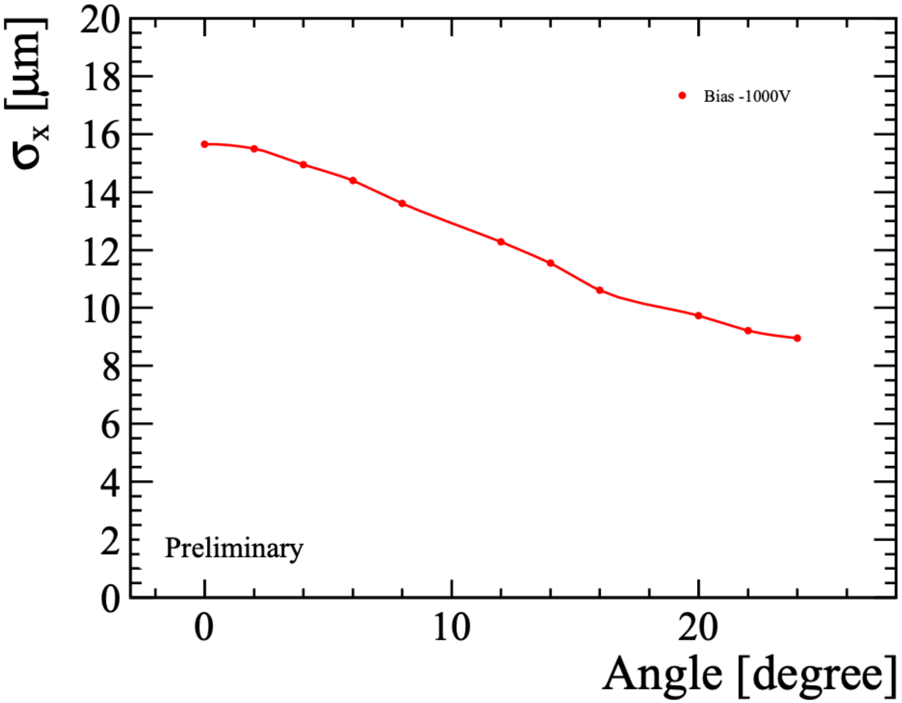
rounded,
DRIE etched
corners



Sensor Resolution



Non-irradiated



Irradiated

Contents

- VELO Overview
  - Layout, Status
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- Cooling
- Services

VELO Cooling

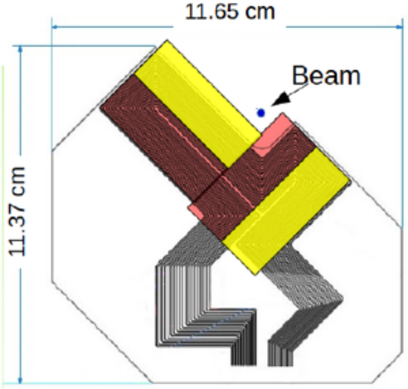
Due to the harsh radiation environment an efficient cooling solution is required to maintain the sensors at < -20°C

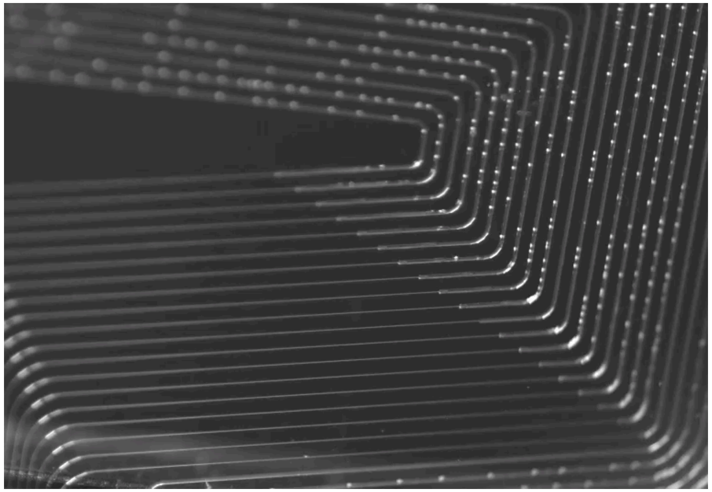
This is provided by the novel technique of evaporative CO_2 circulating in 120 µm x 200 µm channels within a silicon substrate.

Total thickness: 500 µm

⇨

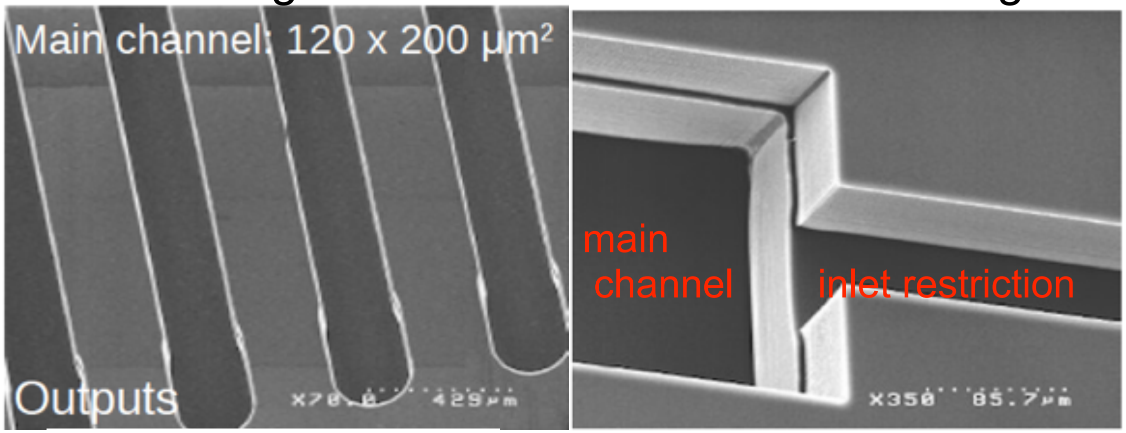
- High thermal efficiency
- CTE match to silicon components
- Minimum and uniform material
- radiation hard





(click for movie)

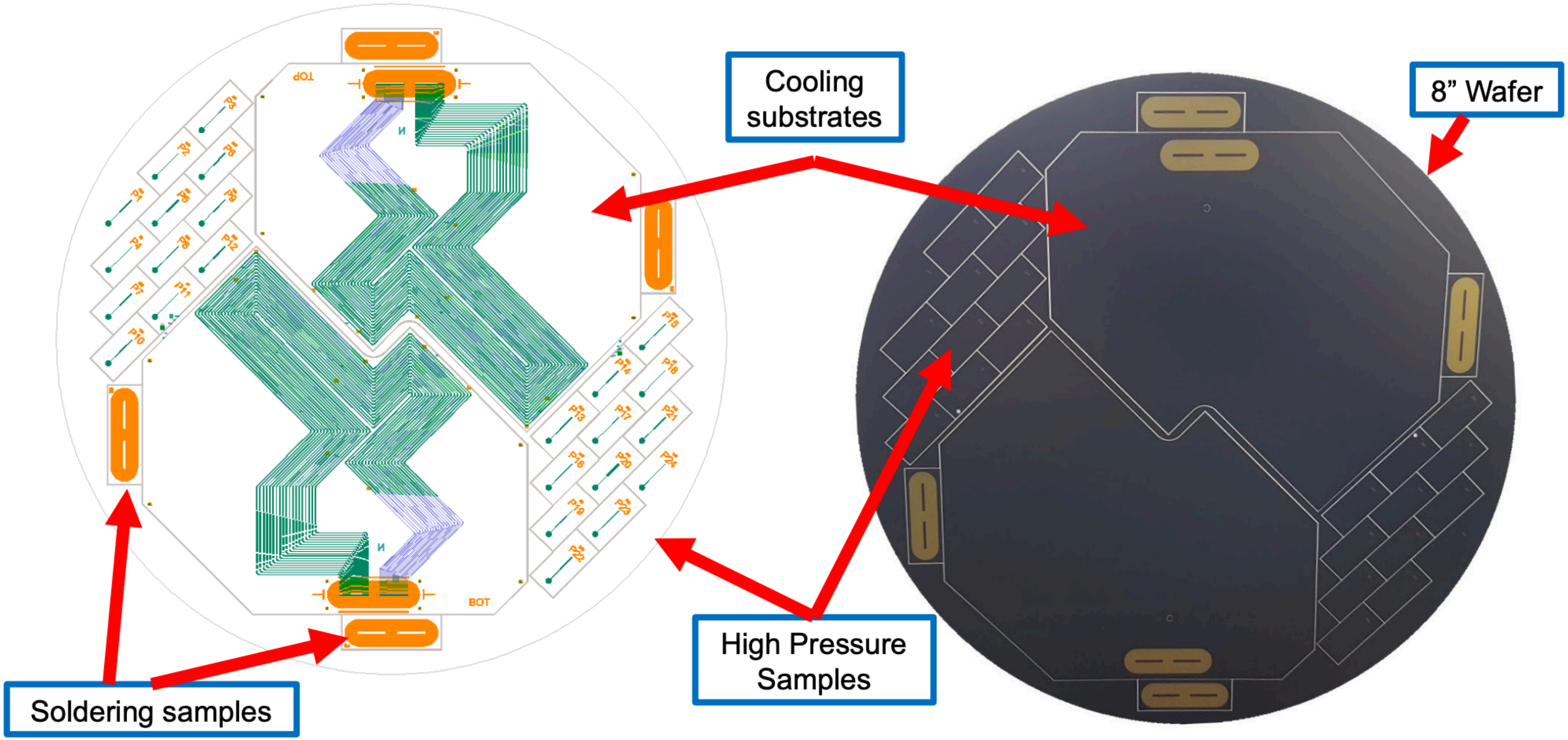
SEM images of etched wafer before bonding



channels output directly to connector

Two step channel etching

Wafer Design



Cooling substrates

8” Wafer

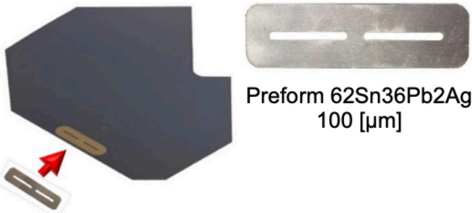
High Pressure Samples

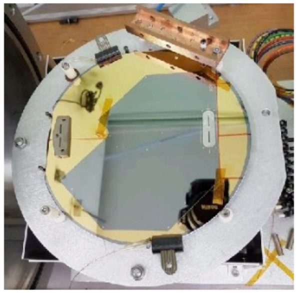
Soldering samples

Fluxless Connector Soldering

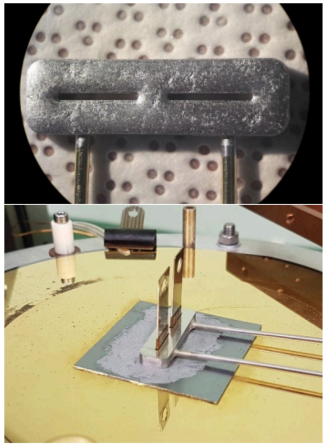
Fluxless process to avoid long term corrosive effects in the cooling system

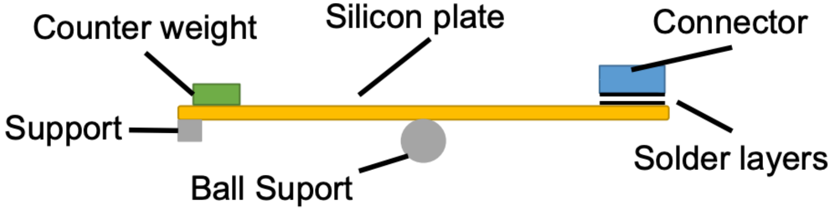
Silicon pretinning

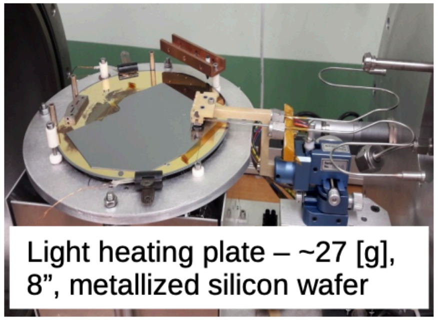




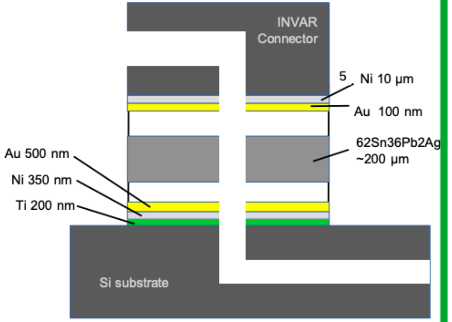
Connector pretinning

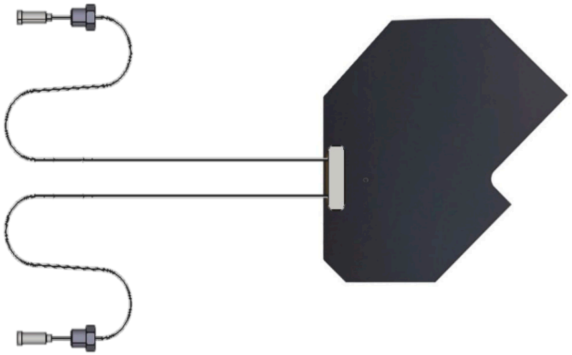






Light heating plate – ~27 [g], 8", metallized silicon wafer



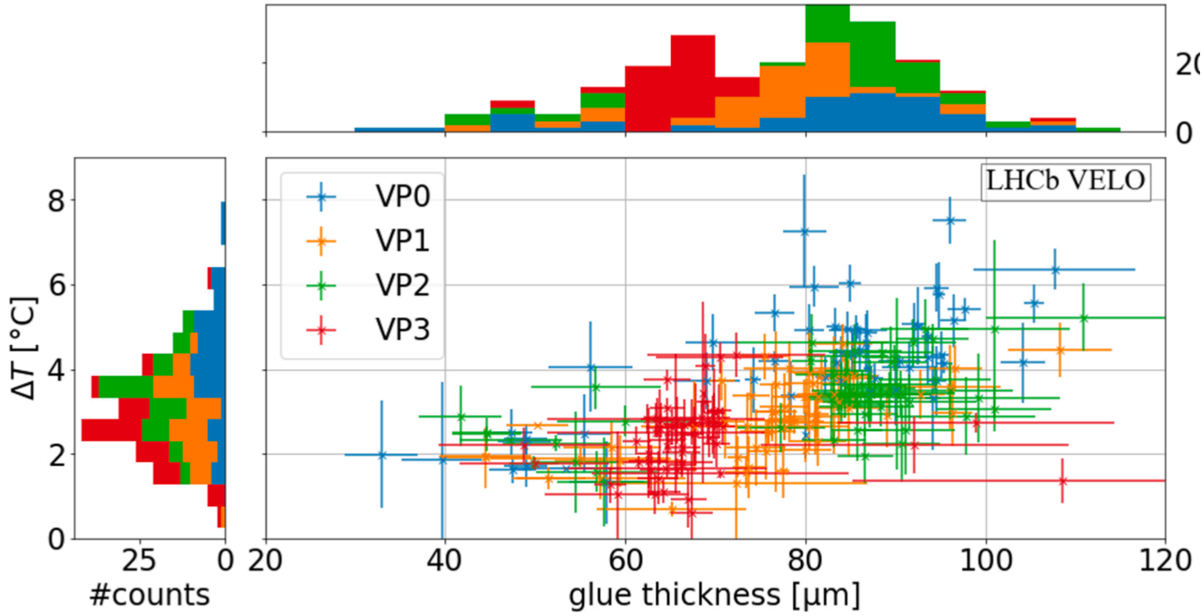


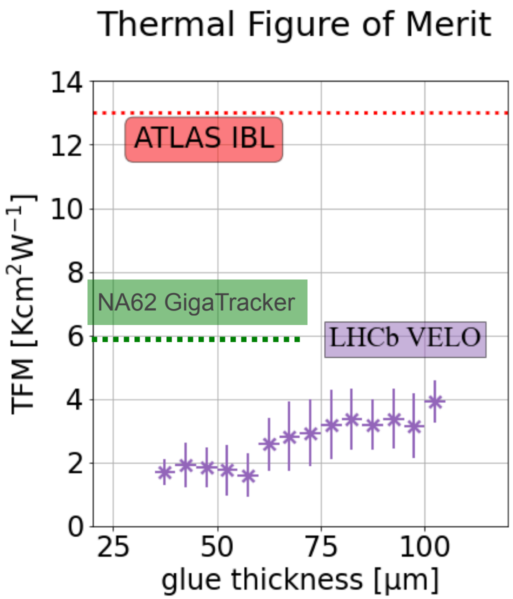
Cooling Performance

The performance of a cooling system can be characterised by the Thermal Figure of Merit;

$$\text{TFM} = \frac{\text{Difference in temperature between coolant and power dissipating element}}{\text{Power Density}}$$

Expected values: ~ 20 for classical systems, ~12-13 for integrated pipe systems, ~5-6 for single phase microchannels



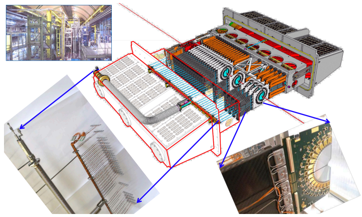

Thermal Figure of Merit

TFM measured value for all produced VELO modules between 2 and 3 (dependent on glue thickness)

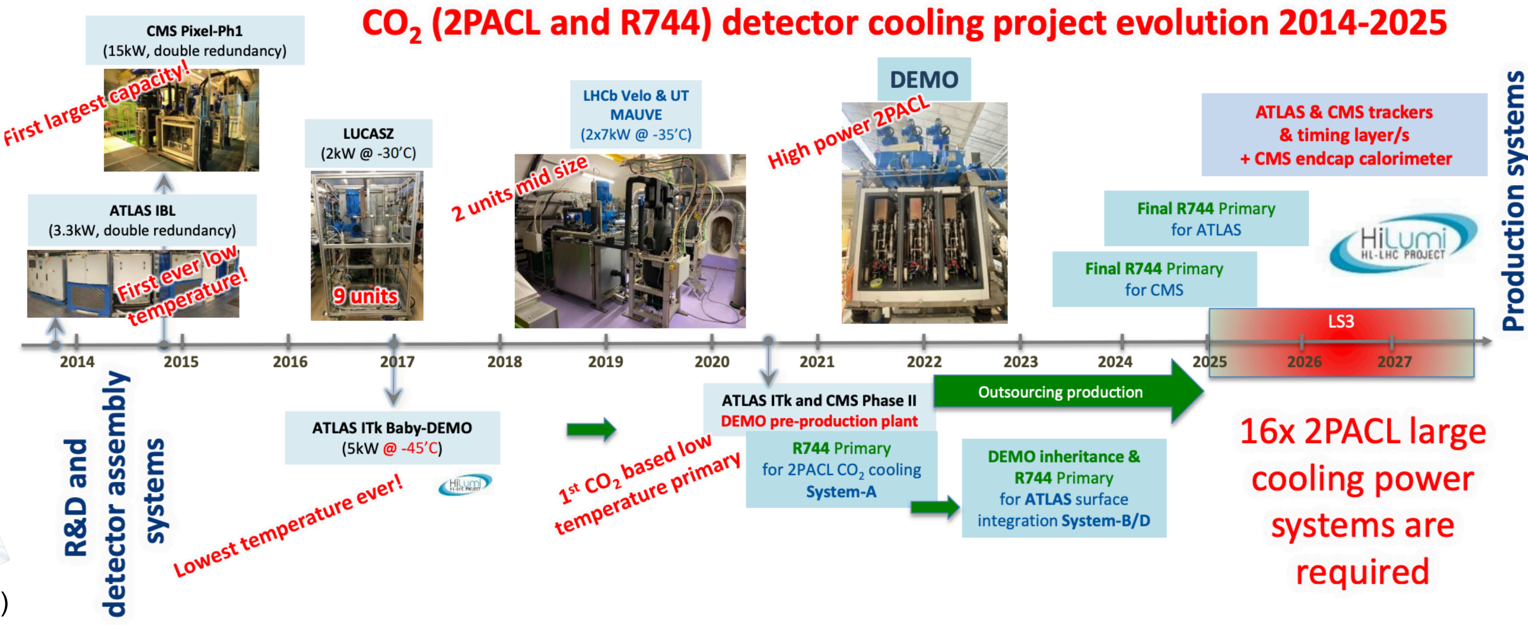
Cooling system evolution

Original 2PACL CO_2 cooling systems

AMS (Alpha Magnetic Spectrometer) NASA project.



LHCb VELO (VErtex LOcator)



MARTA system available commercially

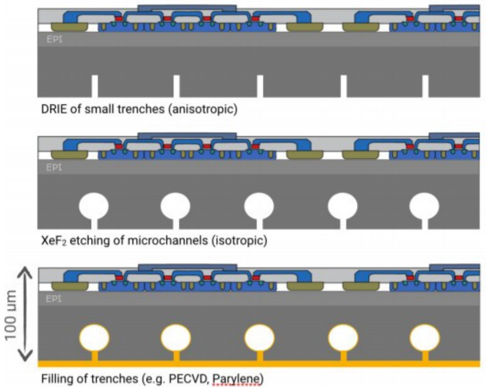
- 200/300/600 W at -30˚C
- http://icp.mech.pk.edu.pl/martaco2/

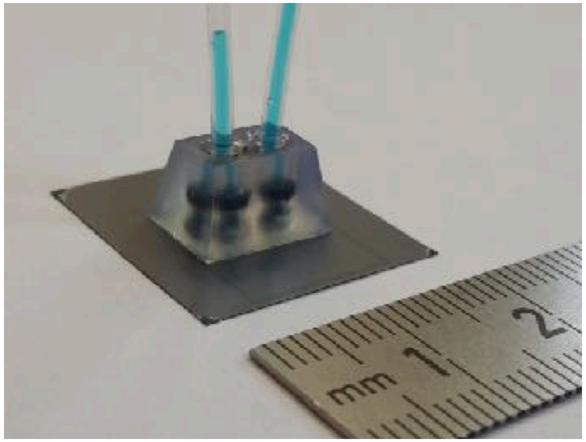
Alternatives to microchannels

Address production cost (yield related)
- Alternative Bonding (anodic bonding..)
- Avoid mask based photolithographic techniques
- Smaller cooling plates

- Handle wafer bonded to active silicon (IFIC/MPI-HLL)
- Buried microchannels (CERN/.EPFL)

[AIDA-2020-NOTE-2020-003]

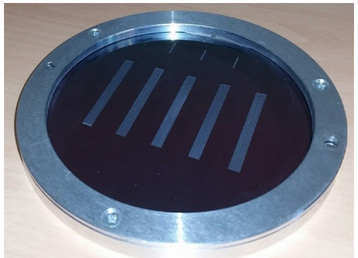


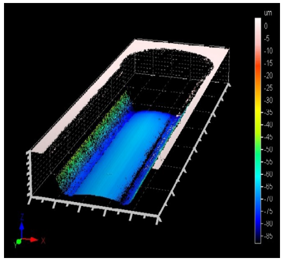


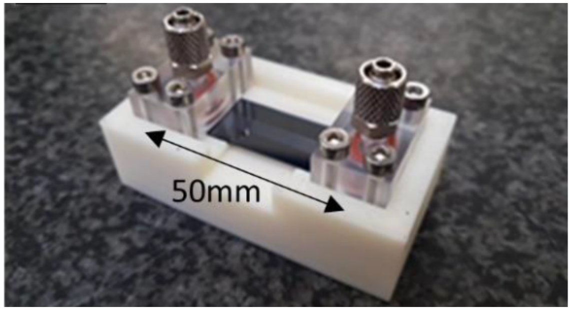
CMOS compatible process
potential post processing step
Holds 110 bars, leak tight to 10^{-8} mbar l/s

Most ambitious approach: bring the cooling to the tiles

R&D @ CPPM
- Laser etching and anodic bonding
- 5 x 10 channels per wafer
- 200µm x 70µm x 4.5cm per channel
- Next step: connector with anodic bonding







Alexandros Mouskeftaras, Stephan Beurthey, Julien Cogan, Gregory Hallewell, Olivier Leroy, et al.. Short-Pulse Laser-Assisted Fabrication of a Si-SiO2 Microcooling Device. Micromachines, MDPI, 2021, 12 (9), pp.1054. 10.3390/mi12091054 . hal-03356892

Alternatives to microchannels

Grade 2 printed Ti: a lot of experience in industry (medical, dental)

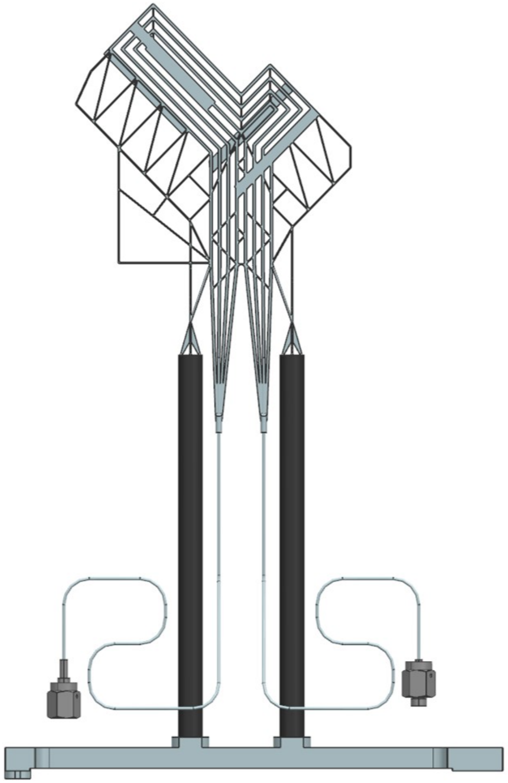
Advantages

- strong, easy to handle, will not break
- easier to connect CO_2 pipes (welding, brazing)
- Restrictions integrated into inlet
- Fast turnaround for design changes (order of weeks)
- Fast production 25/batch, 1 batch/few days
- cheap (<500 Euro / module, including welding capillaries)

Challenges

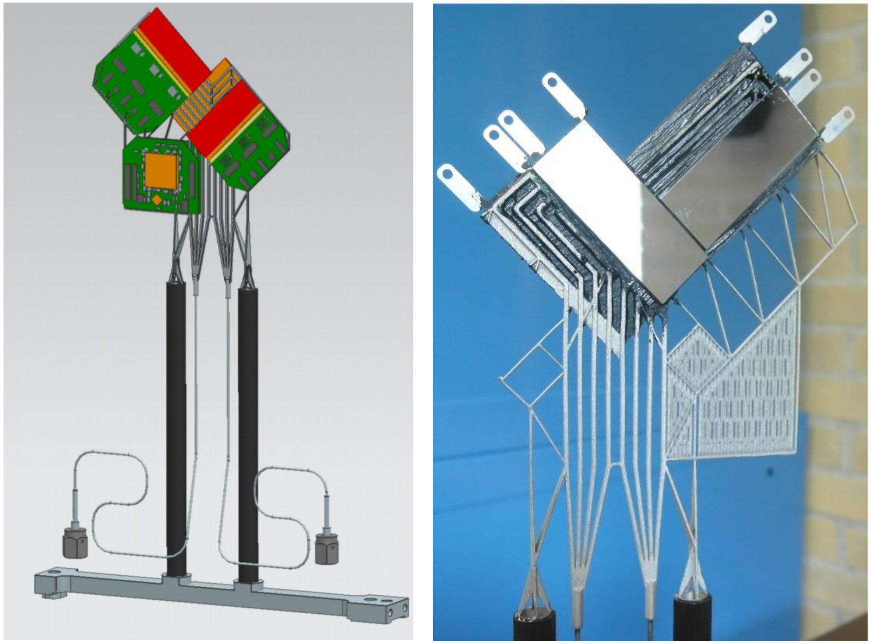
- CTE match with silicon is worse (8.6 vs 2.6 ppm/K)
- smaller thermal conductivity (16 vs 150 W/mK)
- smaller radiation length (3.6 vs 9.4 cm)
- irregularities in printing; less flat surfaces?

3d printed cooling design

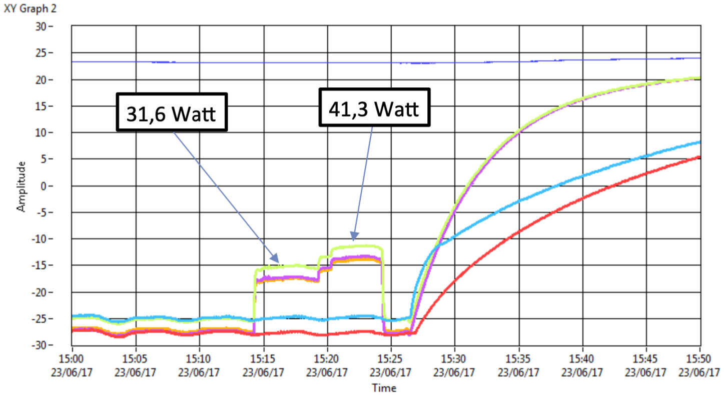


See presentation by Freek Sanders, "Design and Production challenges for the LHCb VELO Upgrade Modules", CERN Detector Seminar, February 2019

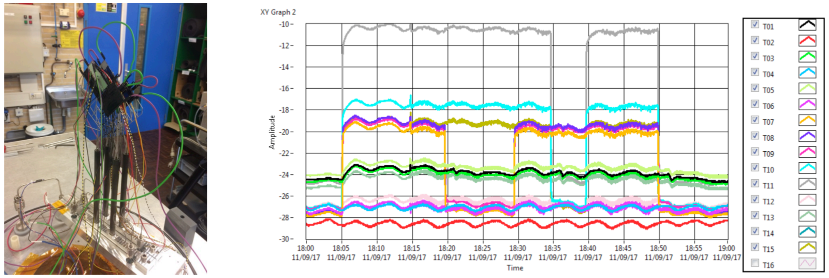
Alternatives to microchannels



prototype fitted with heaters
- high pressure test to 250 bar
- Leak tight with 250 µm wall



successful cooling test (ΔT~13°C)

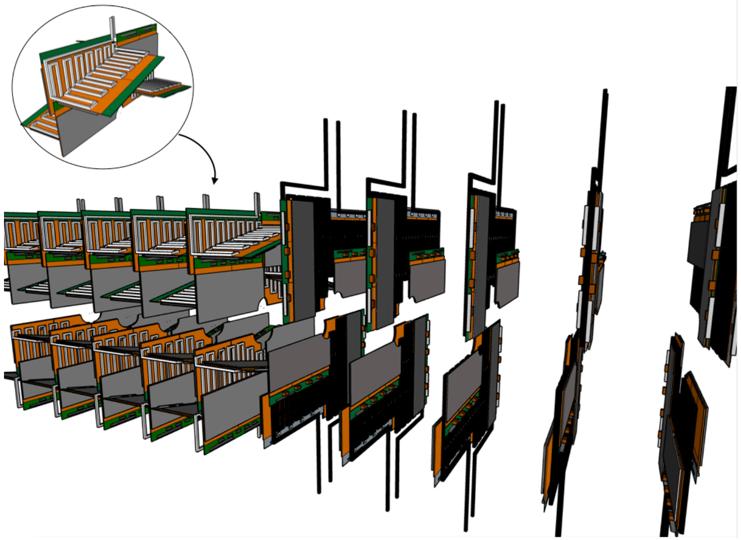


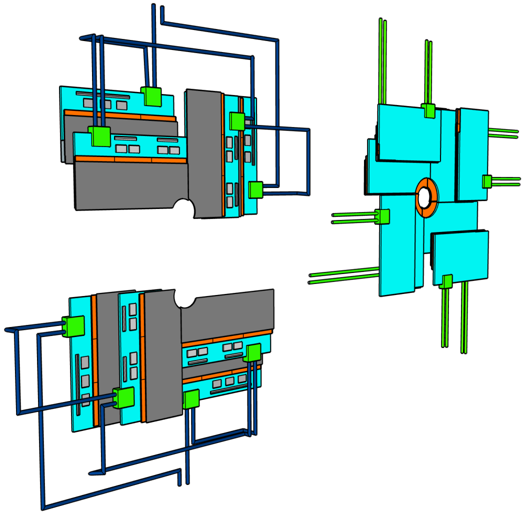
successful flow and stability test (ΔT~13°C)

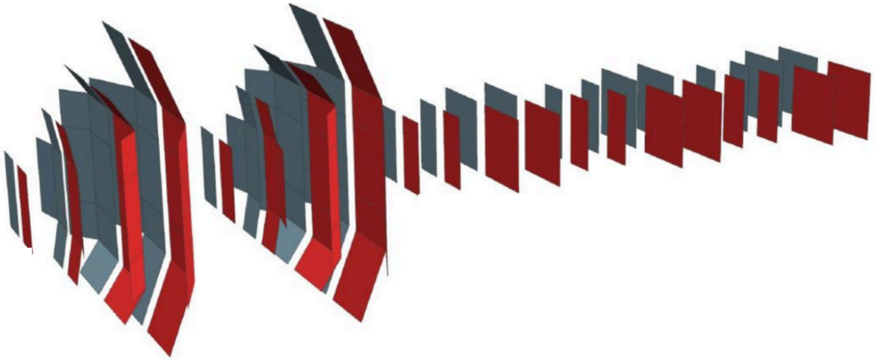
A bit of history

R&D 3d printed substrates made extremely rapid progress and were a credible backup alternative for LHCb. At the time of development the microchannels were sufficiently mature to be chosen as the implementation for Run3

Many types of geometry possible…







3d printed technology already in active development for UII
May give the flexibility required for a cooling “skeleton”
Many issues of connectivity to be solved

Contents

- VELO Overview
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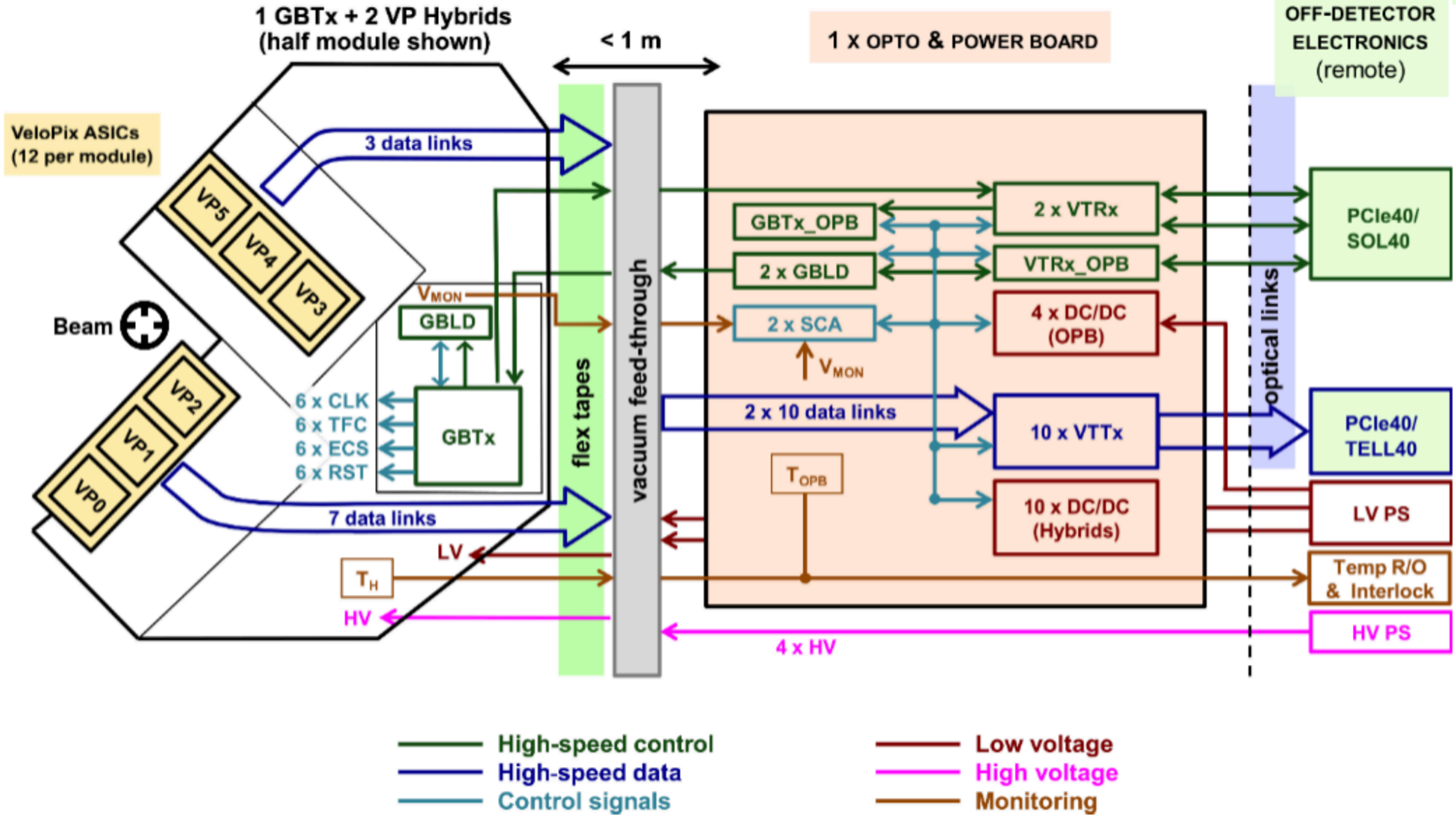
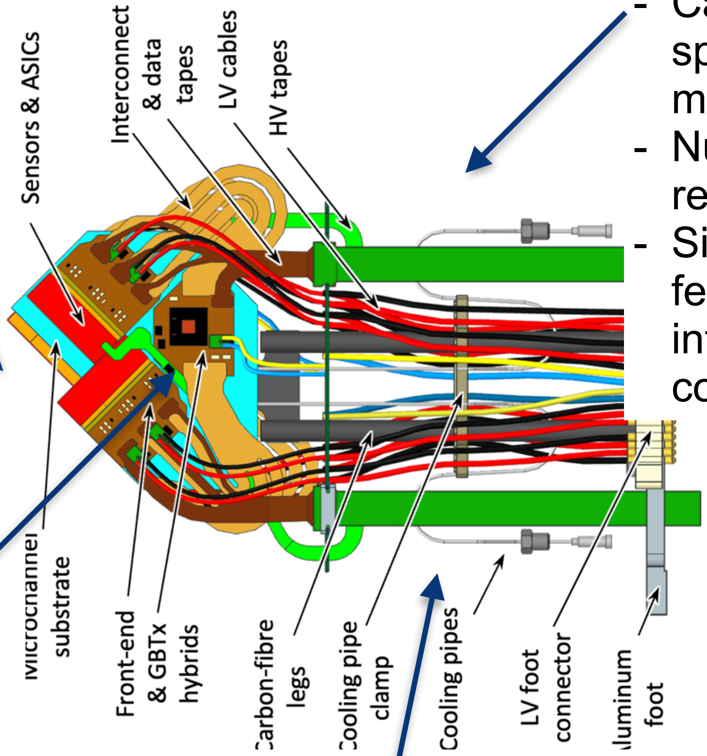
DAQ chain overview



Go with VeloPix?

Shape of front end module no longer appropriate (?)
Can be replaced with single bonded ASICs and sensors

High Speed datatapes
- no longer needed (low mass requirement is gone)
- Can be replaced with high speed cables and cheaper, more reliable connectors
- Number of links may be reduced
- Simplifies design of vacuum feedthrough (extremely labour intensive or expensive component)



Front end hybrids and GBTX hybrids can be replaced with simple flex circuit (no active components, GBTX available). Wire bonded sensor or mezzanine

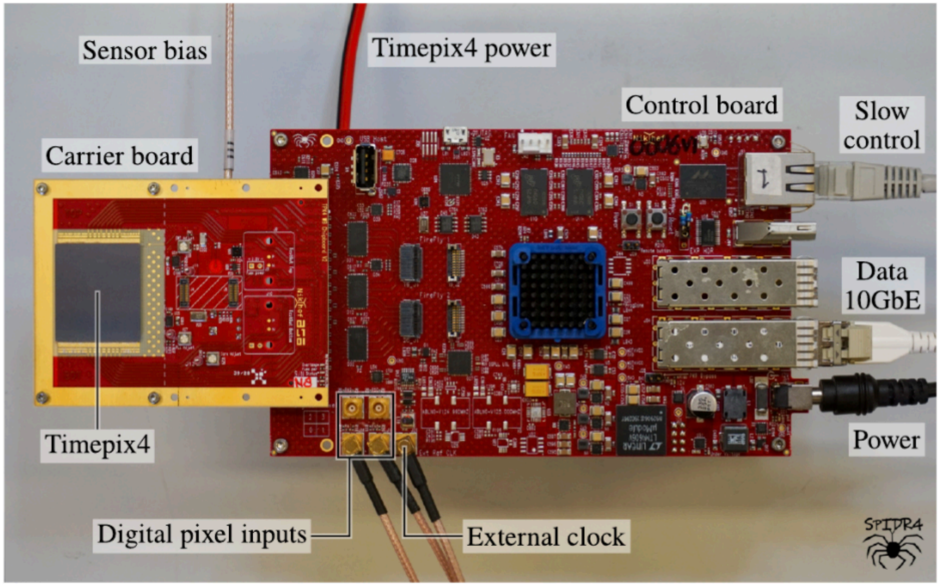
- OPB - new design could be simplified; GBTX → DCDC control
- key question: complexity of reproducing LHCb online environment

Cooling implementation dependent on vacuum/ no vacuum (feedthrough/power)
minimal active cooling may be enough if low temps are not needed

Go with Timepix4?

Timepix4 based hybrid detector

			Timepix4 (summer 2019)
Technology			65nm – 10 metal
Pixel Size			55 x 55 µm
Pixel arrangement			**4-side buttable** **512 x 448**
Sensitive area			**6.94 cm^2**
Readout Modes	Data driven (Tracking)	Mode	TOT and TOA
		Event Packet	64-bit
		Max rate	3.58x10^6 hits/mm^2/s
		Max Pix rate	**10.8 KHz/pixel**
	Frame based (Imaging)	Mode	CRW: PC (8 or 16-bit)
		Frame	Full Frame (without pixel addr)
		Max count rate	~5 x 10^9 hits/mm^2/s
TOT energy resolution			**< 1Kev**
Time resolution			**~200ps**
Readout bandwidth			≤163.84 Gbps (16x @10.24 Gbps)
Target global minimum threshold			<500 e$^-$

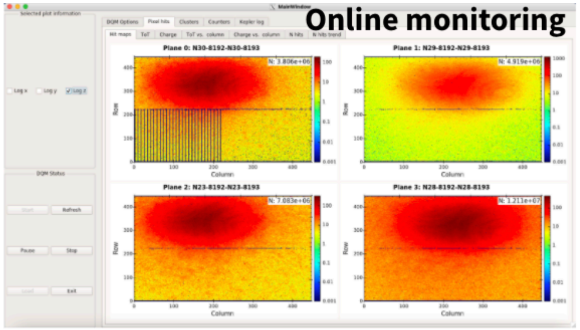


- **TPX4 available with various sensor flavour**
- **SPIDR4 readout system developed by Nikhef:**
    - carrier board + control board + DAQ server with PCIe (160Gb/s for 1TPX4 or 20Gb/s for 12TPX4)
- **ECS and DAQ exist but work to integrate it in an experiment needed**

Go with Timepix4?

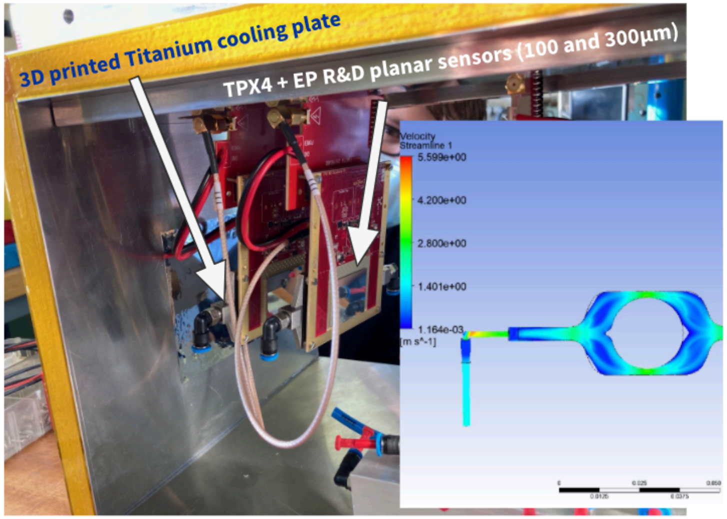
TPX4-based 4D telescope

- **Collaboration** with Nikhef, Uni. of Santiago, Uni. of Oxford, Uni. of Dortmund, Uni of Manchester
- Expect **30-40ps per track** in first phase (end 2022) and **25-30ps in second phase** (end 2024)
- **Pointing resolution** @DUT down to **2µm**
- **No rate limitation** (TPX4 up to 358MHz/cm^2, hit based)



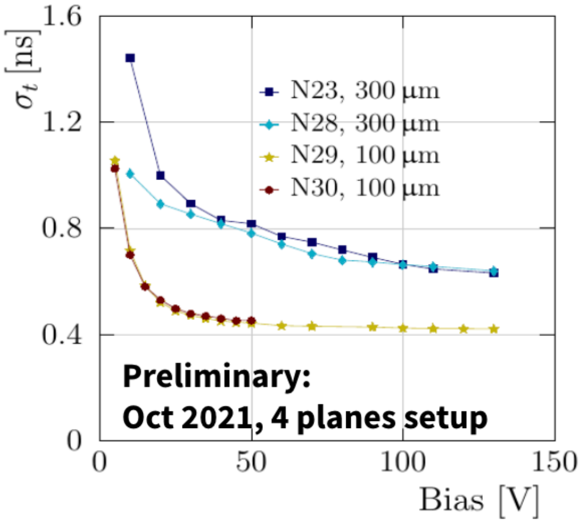
Online monitoring

Double arm prototype in beam in July



3D printed Titanium cooling plate

TPX4 + EP R&D planar sensors (100 and 300µm)



Preliminary:
Oct 2021, 4 planes setup

Thank you!