A Silicon Vertex Detector with Timing for the Upgrade II of LHCb

International Workshop 23rd iWoRiD on Radiation Imaging Detectors

23rd International Workshop on Radiation Imaging Detectors

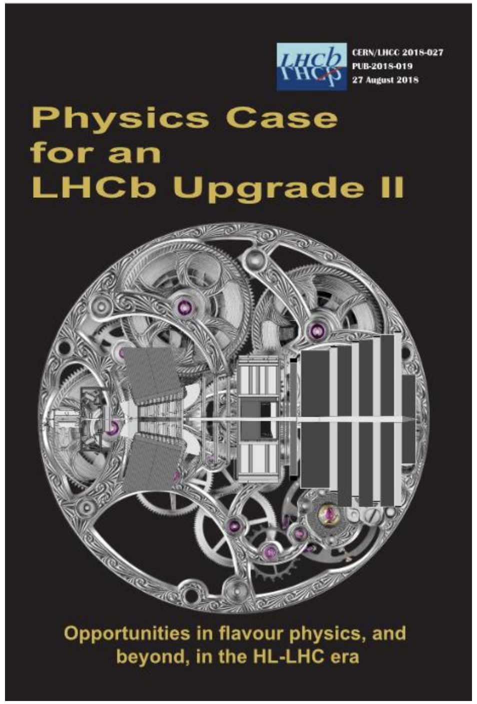
Jakob Haimberger on behalf of the LHCb VELO group

Motivation

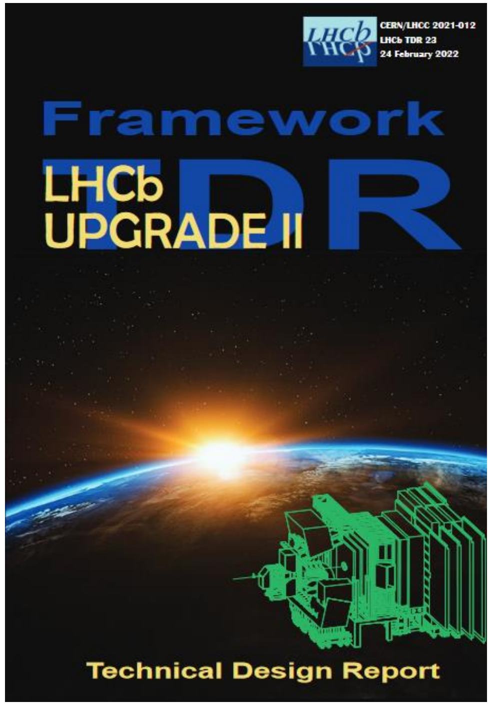
LHCb detector is fully equipped in the forward region, precision measurements of decays of b and c hadrons

Future Goals:

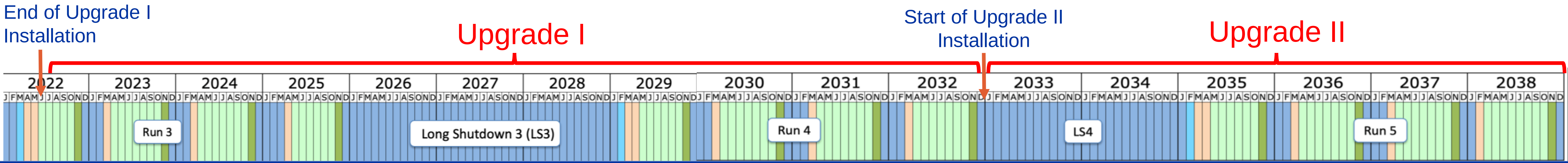
- Bigger data samples to study **rare decays** and **improve uncertainty** for existing ones
- **Extended physics case** in flavor physics and beyond



Upgrade II physics case

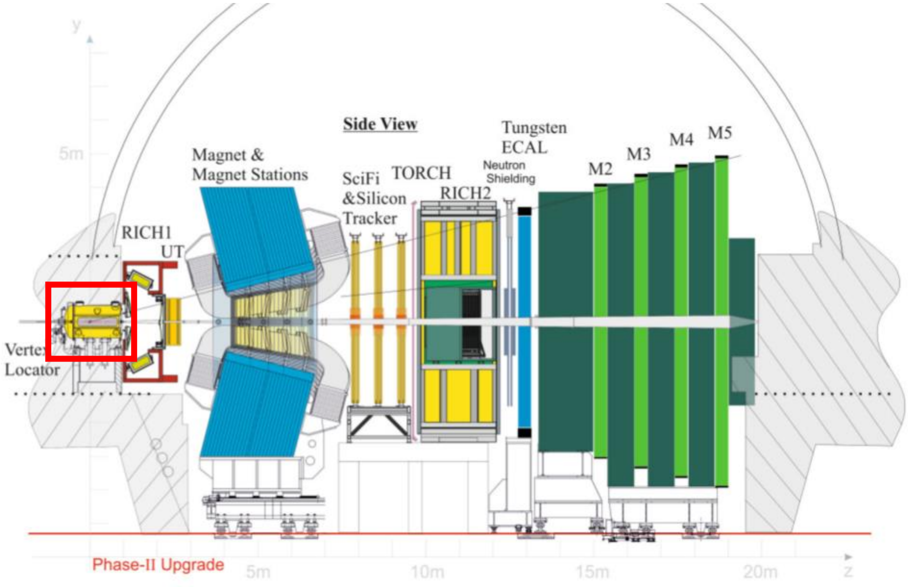


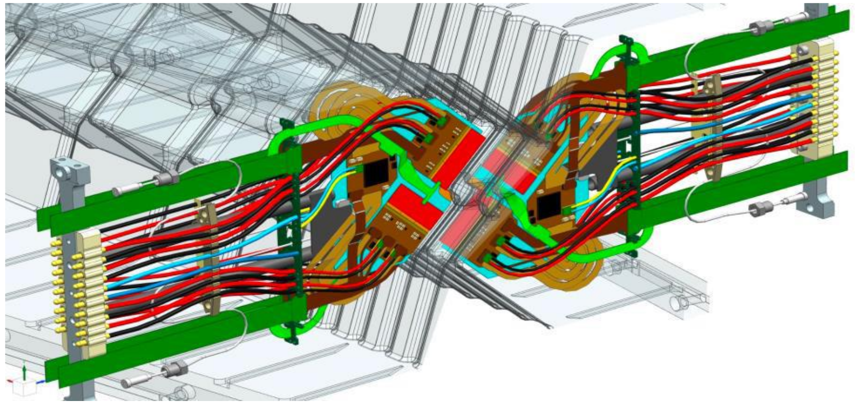
Upgrade II TDR



VErtex LOcator (VELO) Upgrade I

- **VELO**: silicon tracker close to the collision point
- Need to distinguish between primary and secondary vertices→ **as close as possible to beam line** (5.1 mm)
- Previous detector readout limited to 1MHz → limitation for hadronic modes when increasing luminosity
- Upgrade I readout: **40MHz** to fully exploit the factor 5 increase in instantaneous luminosity





Upgrade II

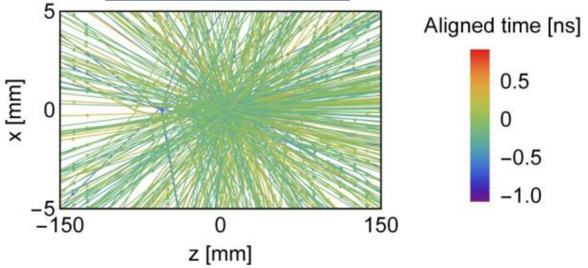
- Make use of HL-LHC Upgrade:
  - **7.5** x Upgrade I instantaneous luminosity
  - **6** x Upgrade I integrated luminosity
- Similar precision compared to Upgrade I to achieve excellent physic performance
- Main challenges:
  - Increased non uniform **radiation damage**
  - Higher **data rates**
- Open R&D paths:
  - Introduction of **Timing**
  - Different **layout scenarios**
  - New **Sensor** and **ASIC technologies**
  - **Material budget reduction**

	Run1 & 2	**Upgrade I**	**Upgrade II**
Inst. Luminosity [$cm^{-2}s^{-1}$]	~4 x 10^{32}	~2 x 10^{33}	~1.5 x 10^{34}
Luminosity / year [fb^{-1}]	2	7	50
Collisions per bunch crossing	1.8	5.5	42
Max Integ. Fluence [MeV_{neq} /cm^2]	4.3x10^{14}	8x10^{15}	6x10^{16}
Readout rate /ASIC [10^6 hits/s]		600	4500

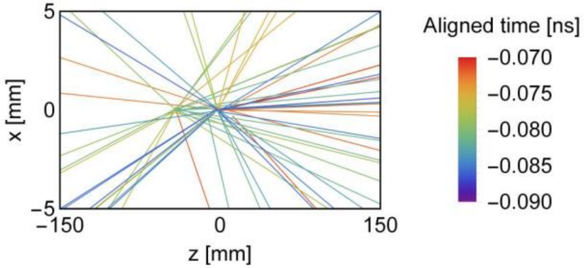
The importance of timing

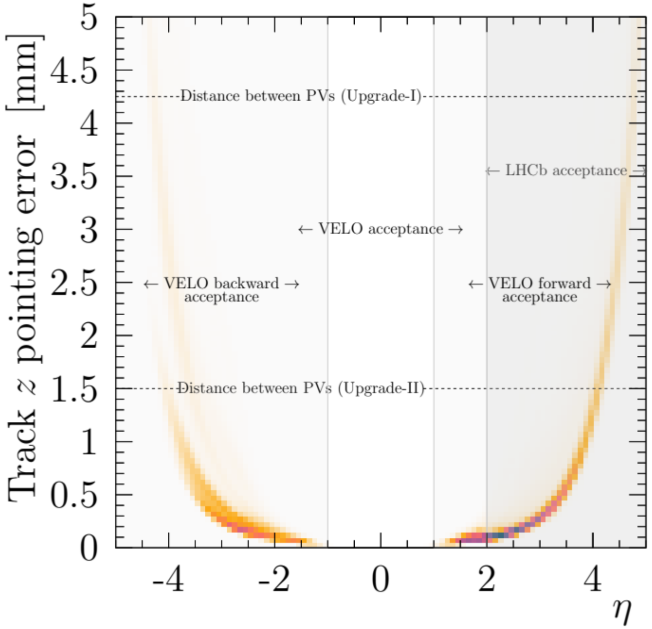
- **Higher pileup** leads to distance between primary vertices close to detector resolution
- Substantial decrease in primary vertex (PV) reconstruction efficiency
- Spread of PVs (RMS) in time ~**180 ps**
- If tracks can be separated in time, we can recover the lost reconstruction efficiency
- Around **20 ps per track** need to ensure same reconstruction efficiency as Upgrade I

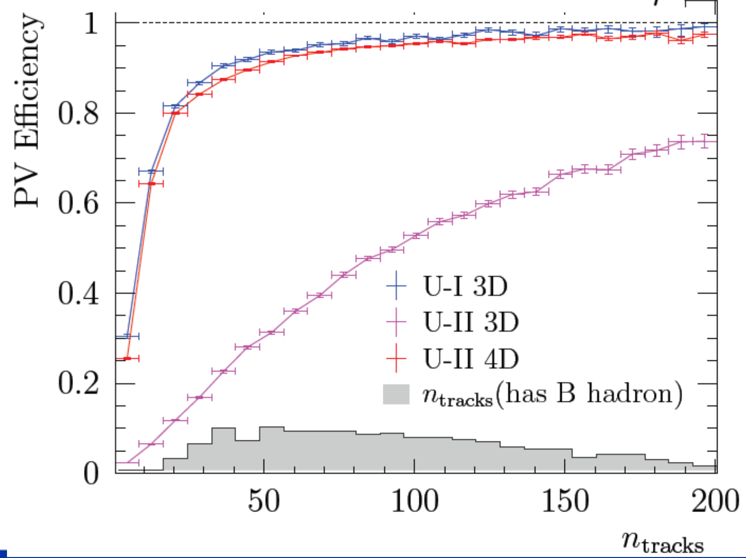
1 ns window



20 ps window



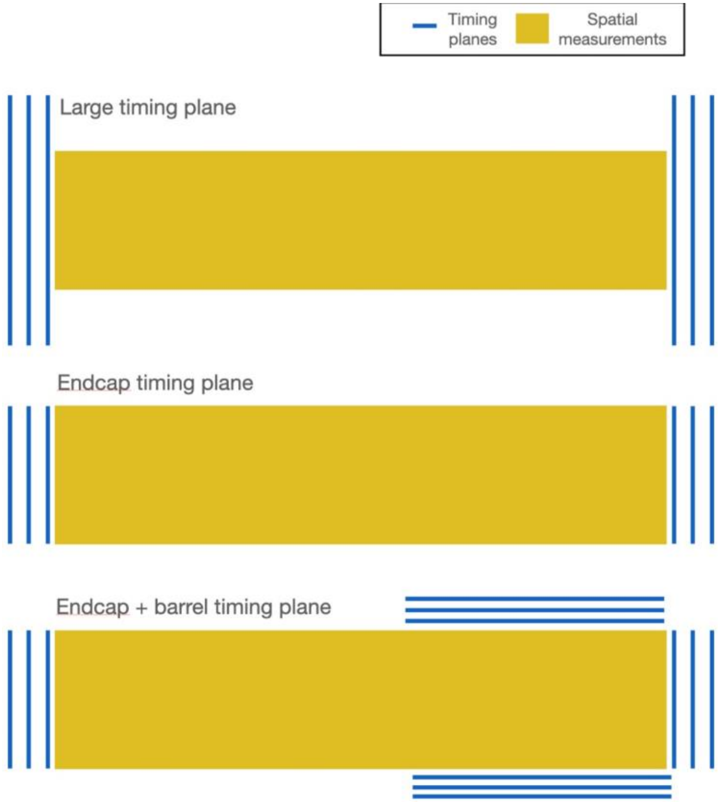




Timing Options 1

Timing Planes:

- *At least **three layers** need for outlier rejection*
- *Far away from interaction point → **less radiation***
- *Single measurement needs at least **25 ps resolution***
- ***Dispersion** due to different particle momenta*
- *Three options considered:*
  - ***Large timing planes***
  - ***Endcap planes***
  - ***Endcap + barrel in forward direction***



	Upgrade I	Large Planes	Endcaps	Endcaps + Barrel
Covered range	$2 \leq \eta \leq 5$	$2 \leq \eta \leq 5$	$2.8 \leq \eta \leq 5$	$2 \leq \eta \leq 5$
Additional area [m^2]	0.1	0.25	0.05	0.4

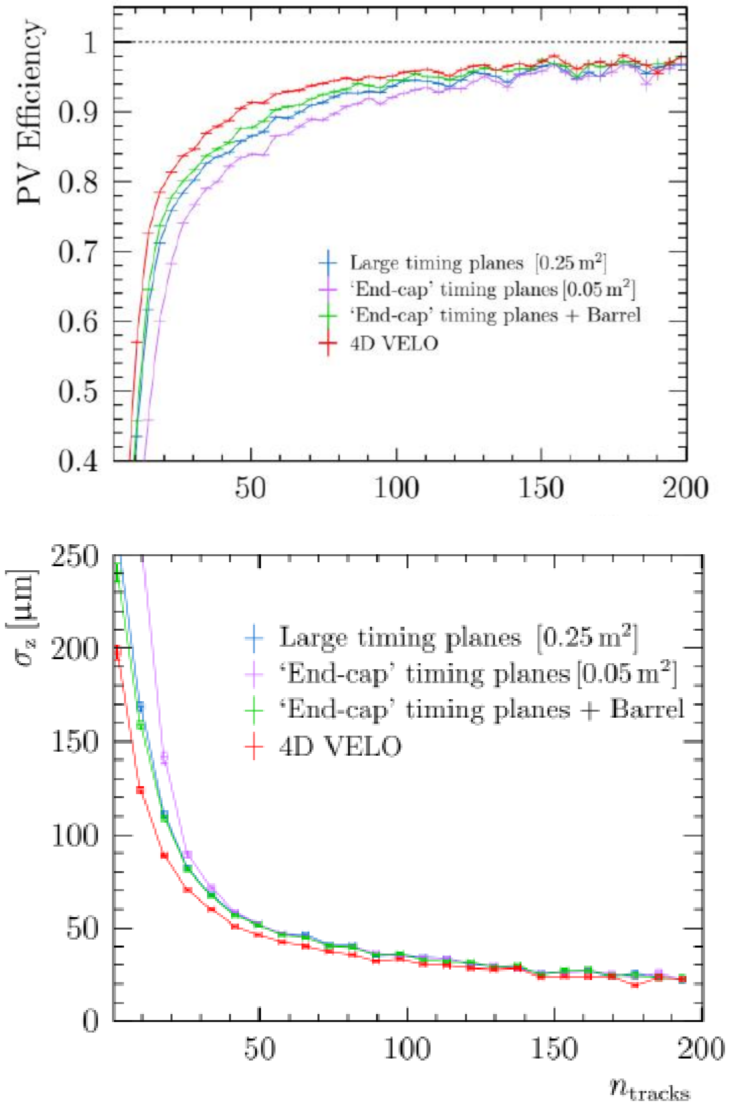
Timing Options 2

4D Tracking

- Single measurement needs at least **50 ps resolution**
- **Better efficiency** in vertex reconstruction and pattern recognition
- Timing needed even in high irradiated region

4D Tracking preferable over dedicated timing planes:

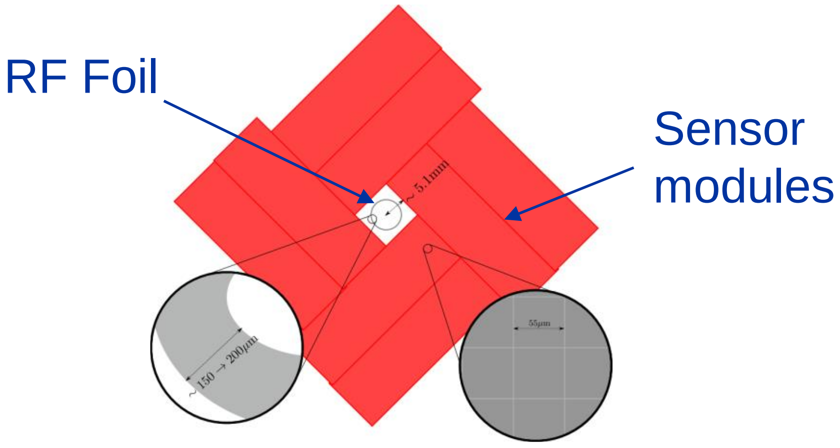
- **Lower cost** due to:
  - No additional sensor area
  - No different ASIC & sensors needed
- **Better reconstruction performance**
  - Better PV efficiency
  - Better PV resolution



Detector layout scenarios for Upgrade II

Scenario A (S_A)

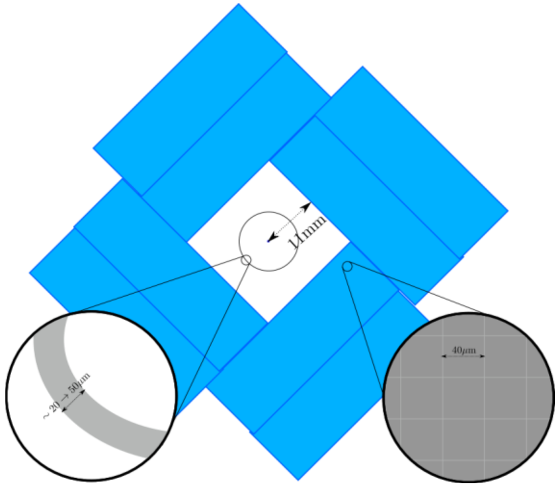
- Distance closest pixel to beamline: **5.1 mm**
- **~9 times higher hit rate (350kHz)** than the VELO Upgrade I
- Either highly **radiation hard sensors /ASIC** or frequent **replacement**
- **6 x radiation damage** as Upgrade I



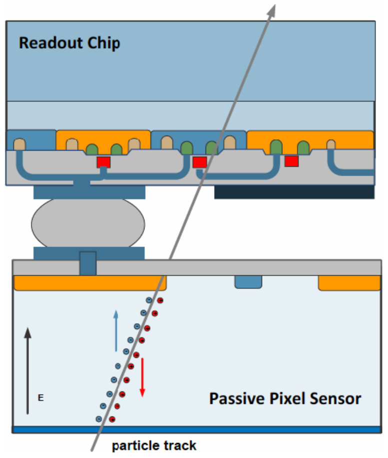
Sketch of a Scenario A using the current sensor modules

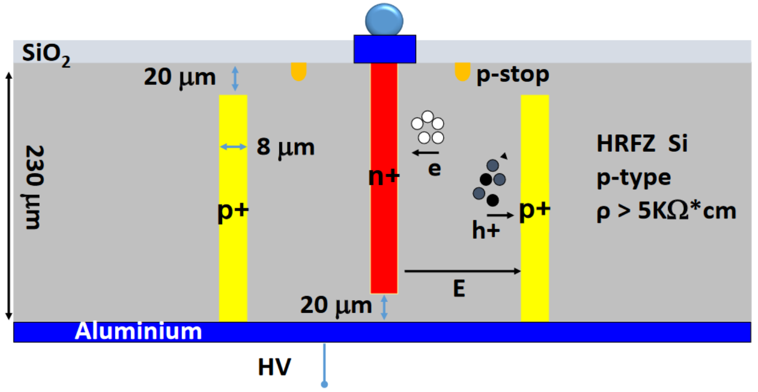
Scenario B (S_B)

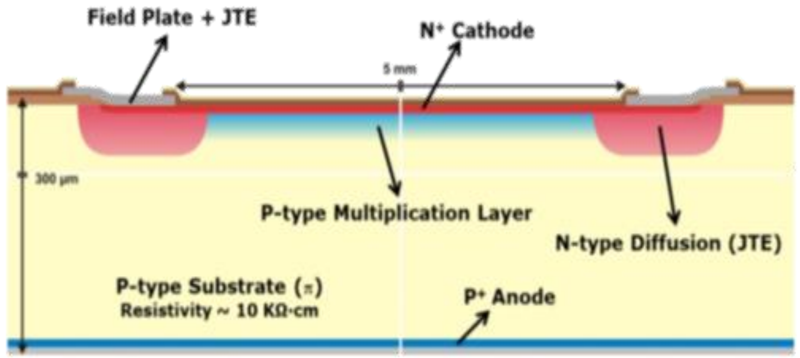
- Distance closest pixel to beamline: **12.5 mm**
- **Same hit rate** as Upgrade I (40kHz)
- Better hit resolution needed → **pixel size < 42 µm**
- **Material budget** needs to be reduced before the second measured point
- **Same radiation damage** as Upgrade I



Sensor technology







Planar Sensors:

Performance depends on thickness. Thin sensors preferable in high irradiation environments.

- 👍 Short collection time
- 👍 Uniform weighting field
- 👎 Low signal to noise ratio

3D Sensors:

Decoupling of charge generation distance and drift distance

- 👍 Timing depended on pixel size
- 👍 Signal proportional to thickness
- 👍 Good radiation hardness
- 👎 Field non-uniformities increase with decreasing pixel size

LGADs:

- 👍 Internal Gain→ high signal to noise ratio
- 👍 Good timing performance due to short high field region
- 👎 After $2x10^{15}$ MeV_{neq} $/cm^2$ loss of gain due to acceptor removal
- 👎 non-uniform irradiation → different gain
- 👎 Segmentation problems at small sizes

ASIC requirements

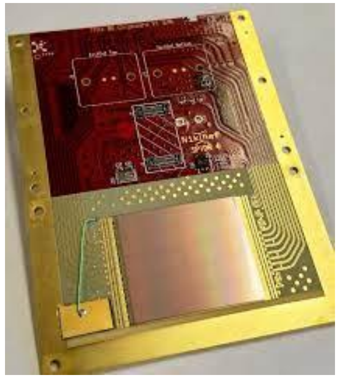
- In both scenarios the ASIC size is independent from the pixel size:
  - **S_A**: Pixel matrix of 256x256
  - **S_B**: Pixel matrix of 335x335
- Listed hit rate assumes a **cluster size** of **2** and **peak rate** of **1.5** times the listed value
- Hit pile up should be kept below 1%:
  - **S_A**: mean time between hits 2.9 µs→29ns discharge time
  - **S_B**: mean time between hits 25µs→250ns discharge time
- Data rate calculations assume a **44 bit** per hit

Requirement	scenario S_A	scenario S_B
Pixel pitch [µm]	≤ 55	≤ 42
Lifetime fluence [1×10^{16} 1 MeV n_{eq}/cm^2]	> 6	> 1
TID lifetime [MGy]	> 28	> 5
Sensor Timestamp per hit [ps]	≤ 35	≤ 35
ASIC Timestamp per hit [ps]	≤ 35	≤ 35
Hit Efficiency [%]	≥ 99	≥ 99
Power per pixel [µW]	≤ 23	≤ 14
Pixel rate hottest pixel [kHz]	> 350	> 40
Max discharge time [ns]	< 29	< 250
Bandwidth per ASIC of 2 cm^2 [Gb/s]	> 250	> 94

ASIC technology

Current: VeloPix developed in collaboration with the Medipix group (130 nm) for Upgrade I

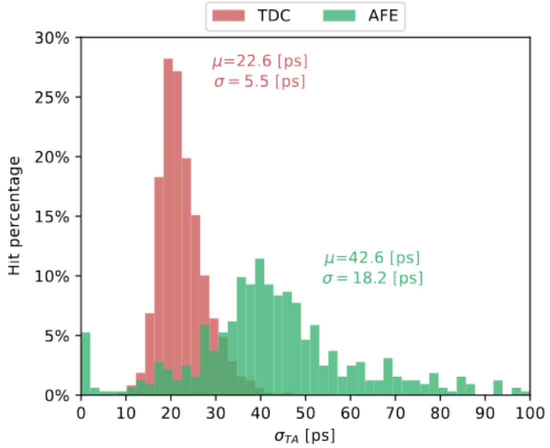
Velopix1:
- **130nm** technology
- **10.44** Gbps/cm^2
- Total time resolution **25** ns
- Power: **<1.5** W/cm^2



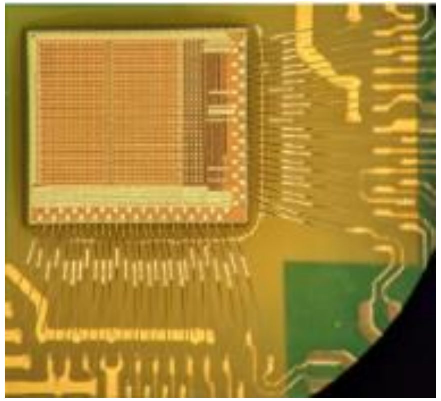
Timepix4 chip

Timespot:
- **28nm** technology
- Minimum pixel size **< 40 µm**
- TDC: ~**23 ps** resolution
- AFE**: ~43 ps** resolution
- Power: **~1.2** W/cm^2

Timepix4:
- **65nm** technology
- **23** Gbps/cm^2
- Minimum pixel size **55 µm**
- TDC: ~**62 ps** resolution
- AFE**: ~ 70 ps** resolution
- Power: <**0.5** W/cm^2



Timespot1 time resolution



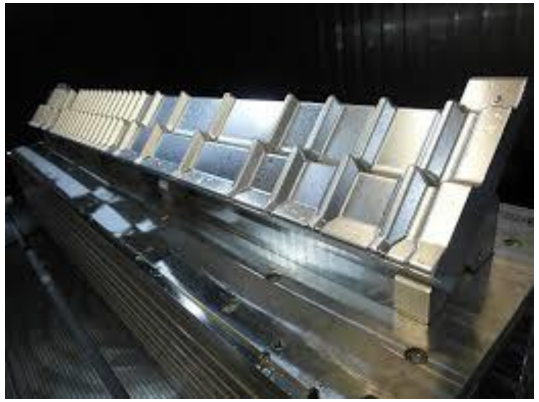
Timespot1 ASIC

PicoPix:
- **In development**
- **Goals:**
  - **28nm** technology
  - **>125** Gbps/cm^2
  - Minimum pixel size **42-55 µm**
  - Total time resolution < **30 ps**
  - Power: **<1.5** W/cm^2

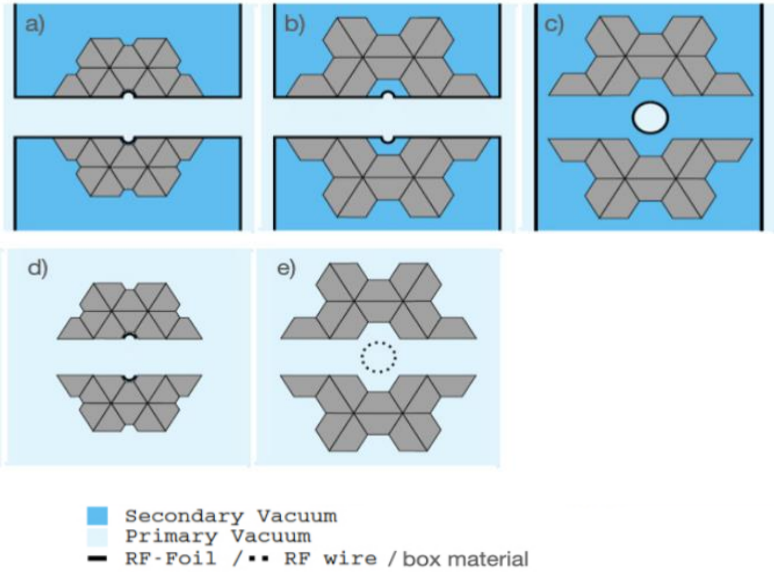
VeloPix II Precursors

RF-Shield

- Conducts **beam mirror current** to avoid wake field excitation
- Shield the detector electronics from **RF pickup**
- Separation between **primary LHC vacuum** and the **secondary detector vacuum** (10 mbar pressure difference)
- Current **corrugated foil** only viable for $\mathbf{S_A}$, as a reduction from 180 to 20 µm thickness needed for $\mathbf{S_B}$ not possible
- New **cylindrical shield** options considered:
  - 2-piece movable foil with secondary vacuum for S_A (a) and S_B (b)
  - Single piece fixed foil secondary detector vacuum for S_B (c)
  - 2-piece movable foil without secondary vacuum for S_B (d)
  - Wire frame to conduct beam current and without secondary vacuum for S_B (e)



Upgrade I RF-foil



Possible Upgrade II foil solutions

Summary

Next 2 years of R&D for LHCb Upgrade II :

- **2 layout scenarios**:
  - **S_A** : extreme high radiation tolerance and high data rate
  - **S_B**: higher precision hit resolution and a reduction of material budget
- Precise timing: needed **resolution** of **20 ps**
  - **4D tracking** preferable over separate timing planes due to better performance and lower overall cost
- **Fast timing sensors** needed to achieve necessary **spatial and temporal resolution**
- **Material budget** must be adjusted depending on the scenario
- New **vacuum tank and cooling system** must be adjusted to keep accommodate Upgrade II changes

Backup

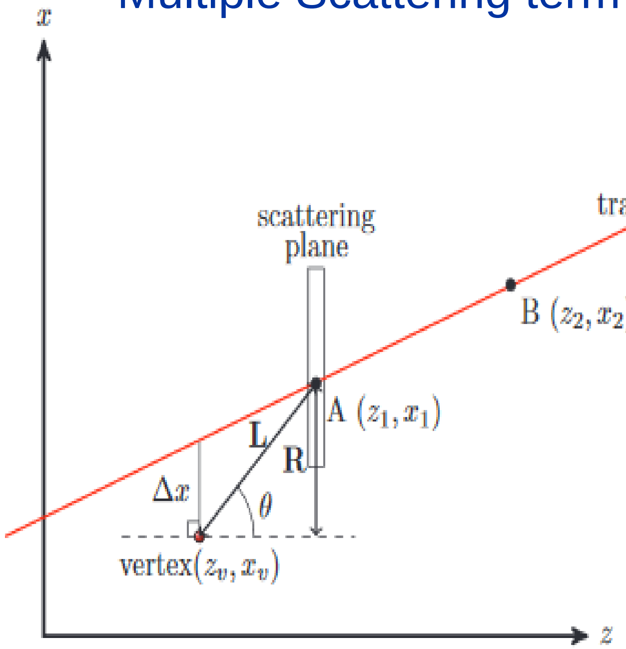
IP-resolution

$$\sigma_{\Delta x}^2 = \frac{\sigma_0^2}{(z_2 - z_1)^2}\left[(z_1 - z_v)^2 + (z_2 - z_v)^2\right] + \frac{R^2}{p_T^2}\left(\frac{13.6MeV}{c\beta} q \sqrt{\frac{x}{X_0}}[1 + 0.038\ln(\frac{x}{X_0})]\right)^2$$

Extrapolation term

Multiple Scattering term

- Increasing inner radius implies:
  - Change of layout
  - Change Material Budget (RF-Foil)
  - Change Pixel resolution



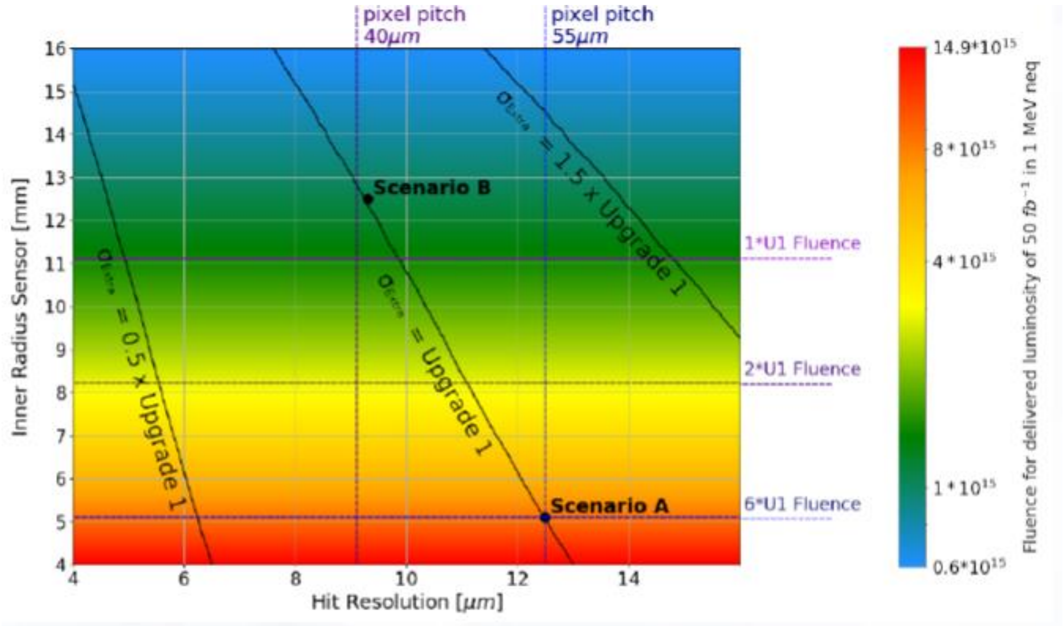
2 Layout Scenarios

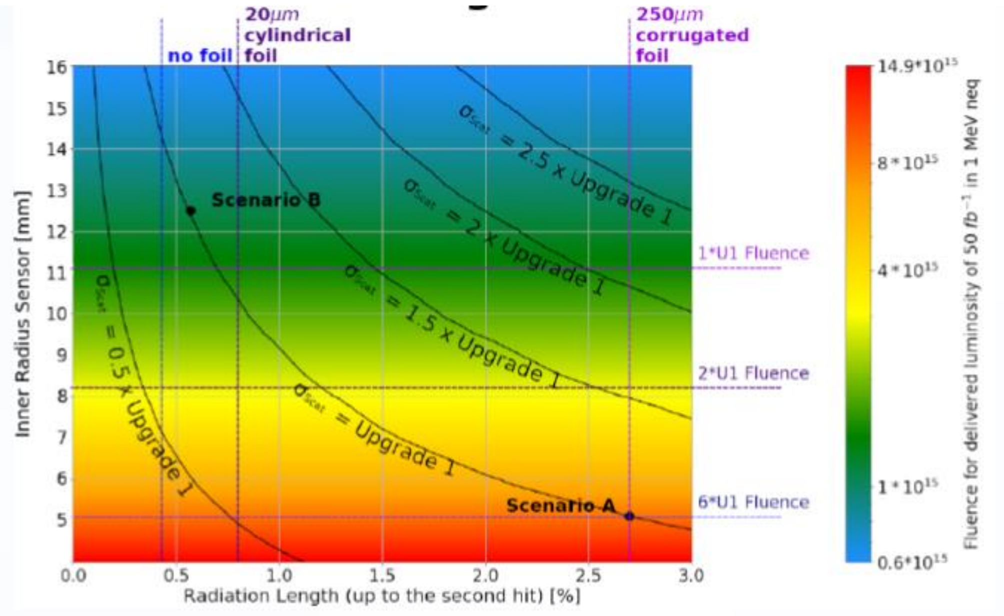
Radiation damage and hit rate can be reduced if sensors are **moved away from the beam** (increased inner radius), **at cost of Impact Parameter (IP) resolution** (closest distance between reconstructed track and PV)

IP resolution can be recovered if **hit resolution** is improved **and material budget** is reduced

Two scenarios which would lead to the same IP resolution:

- **Scenario A**: the sensors stay in their Upgrade I position
- **Scenario B**: the sensors are moved away until they receive the same hit rate & radiation damage as Upgrade I

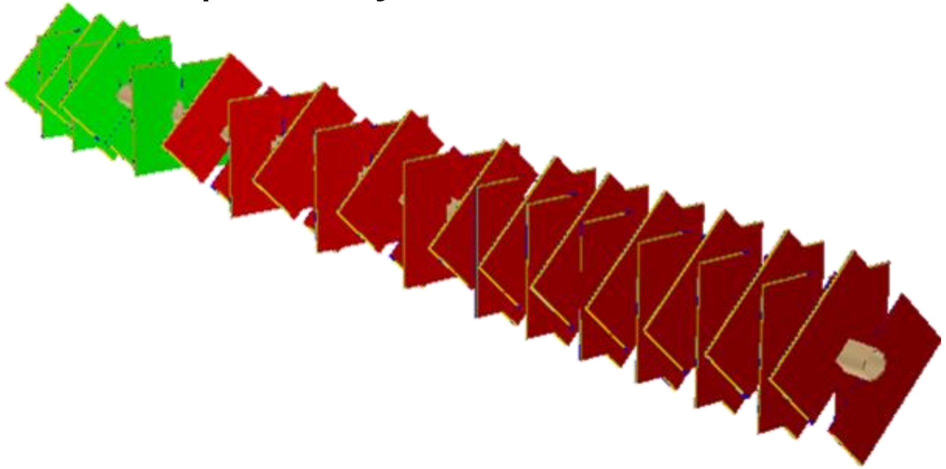


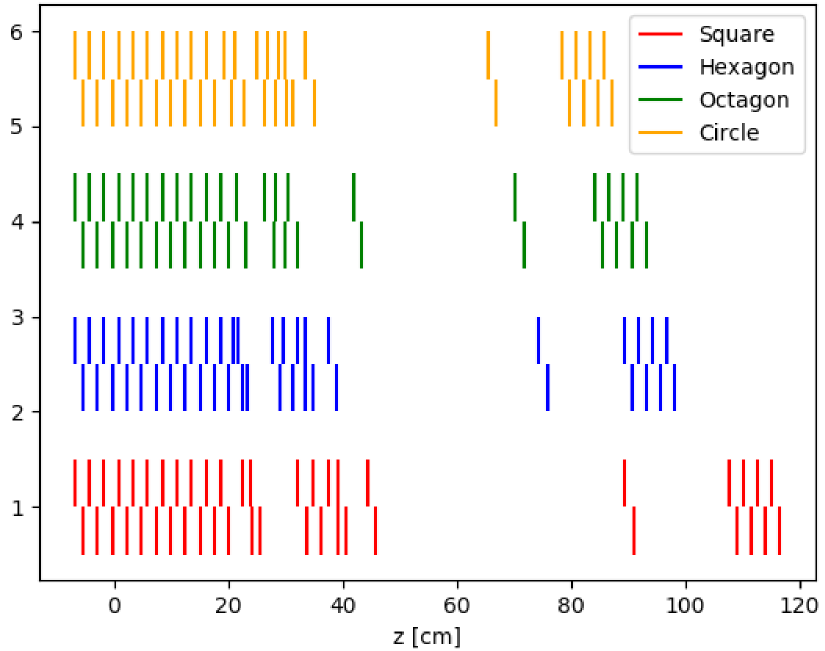


Parametric estimate of IP resolution changes for different inner radii, hit resolutions and material

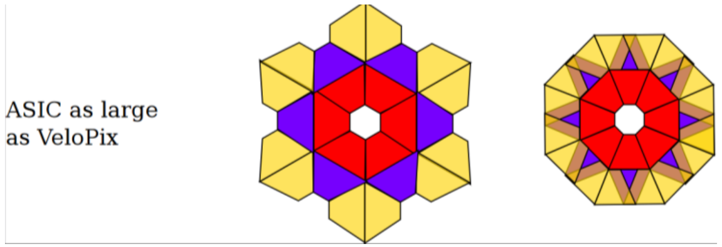
Detector Length

- Detector size depending on value of maximal radial distance of the first hit to the beam(r_{max})
- r_{max} depending on shape of inner hole
- The Octagon can also be approximated by using square tiling and rotate every second plane by 45°

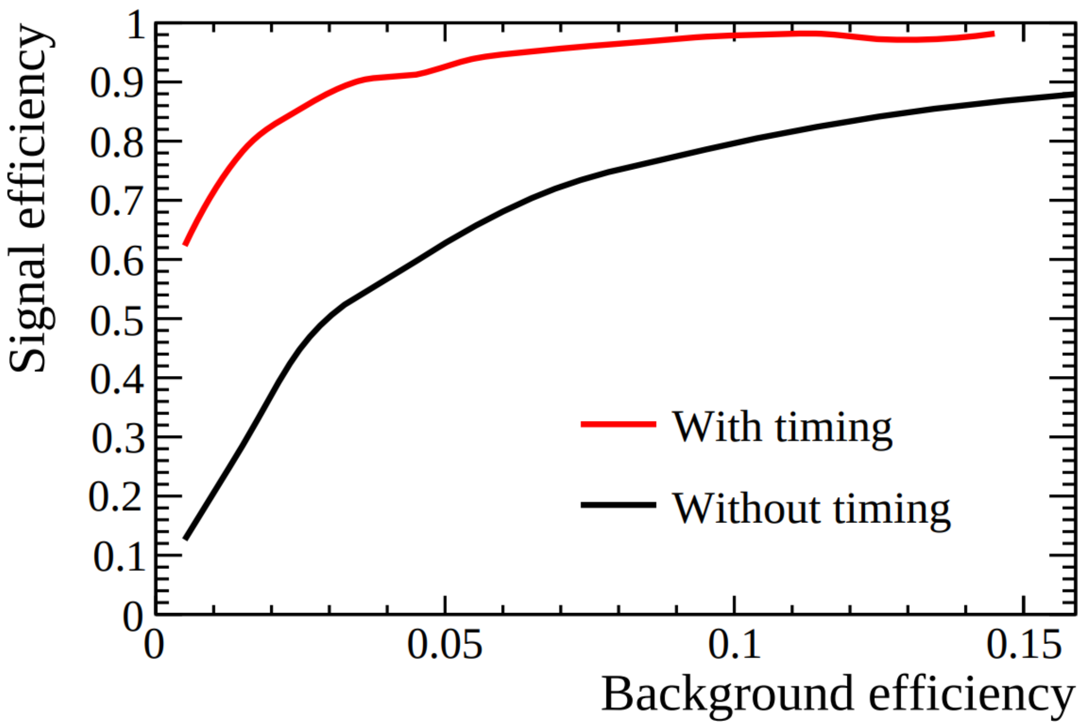


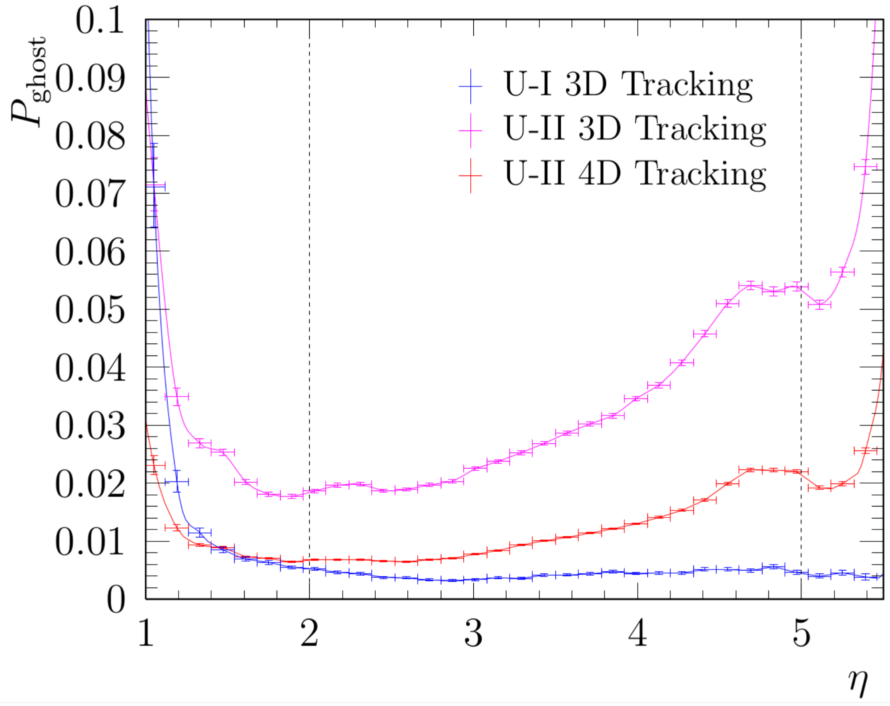


Calculated Layouts for different inner hole shapes



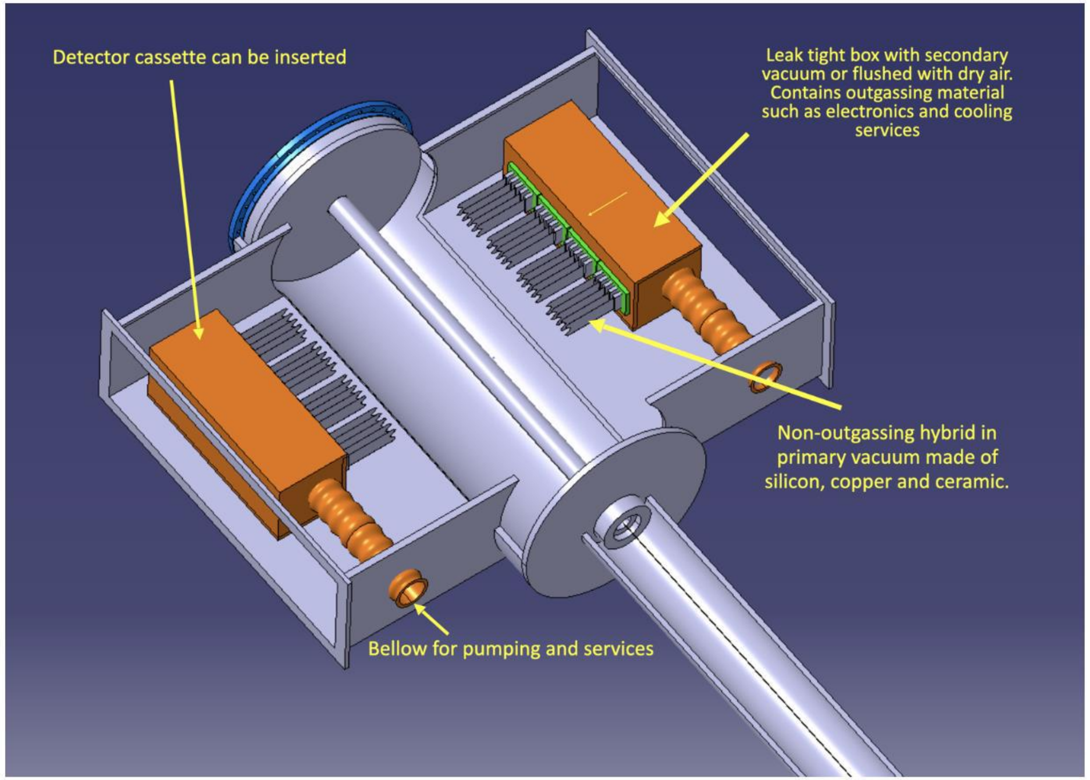
Reconstruction with timing





Vacuum tank

- Needs to be redesigned depending on the scenario
- Needed changes:
  - **Scenario S_A:**
    - Possibility to change the Modules after a certain amount of time
  - **Scenario S_B :**
    - Better vacuum and bakeout resistance if no RF-foil is used
    - Inclusion of a static cylindrical RF-foil

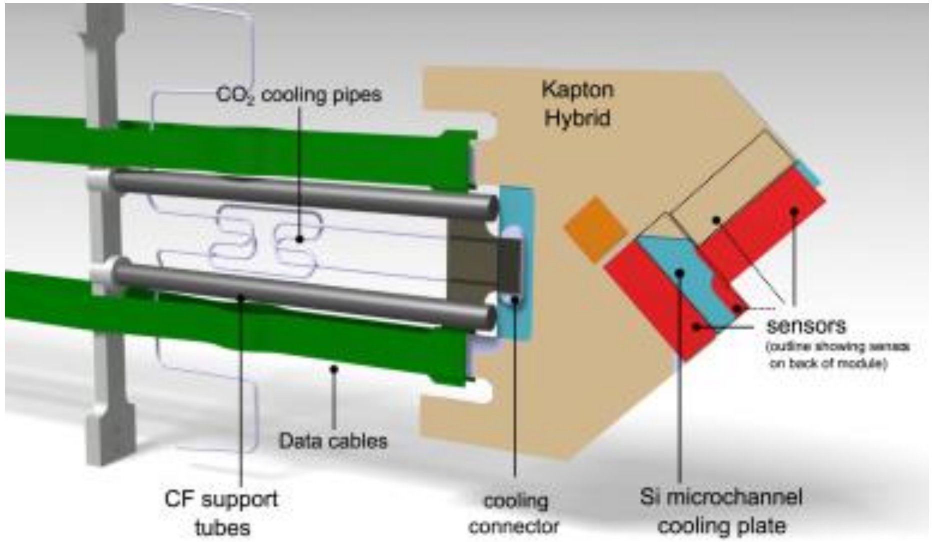


Possible no foil vacuum tank

Cooling

- Cooling is necessary to prevent **thermal runaway** caused by leakage current and to avoid **annealing** of the irradiated sensors.
- Power budget expected to be a least 1.5 W/cm^2 (same as Upgrade I)
- **Upgrade I:**

  CO_2 cooling via silicon micro channel plates
- **Upgrade II:**
  - New coolants such as Krypton are needed to allow cooling below -40°C
  - Two phase cooling
  - Alternative substrate solutions involving 3D printing silicon carbide or titanium reduce costs



Upgrade I cooling