The LHCb VELO Upgrade - sensor R&D with the Timepix3 Telescope

Precision of many physics measur-ements at LHCb will be statistically limited at end of Run 2 | Boost statistic with increased L(4×10³² \rightarrow 2×10³³) cm^{-2} s⁻¹ | 25 fb^{-1} expected in Run 3 | But many hadronic channels saturate due to energy cuts in the trigger | Remove hardware trigger \vert 1*MHz* \rightarrow 40 *MHz* readout rate with software trigger only | Data taking in Run 3 starting 2021 [1].

Timepix3 telescope performance entitled assessment in Sensor characterization Test
 beam

The Timepix3 telescope is a high rate, data-driven beam telescope originally built to test the prototype sensors for the LHCb VELO upgrade, but also employed by other users due to its excellent performance. It provides a fast and robust pattern recognition α_{PQ} , as as assembly prototype. and track reconstruction.

Upgrade motivation

Spatial resolution

High rate Serve Resolution Resolution telescope a reasonable pointing precision \mathbf{r}

over the entire pixel cell. Assemblies irradiated at full fluence $\approx 12000 \left[\frac{1}{2} \right]$ \rightarrow HPK n-on-p $\sum_{n=10000}^{\infty}$ $\frac{1}{n}$ corresponding bias voltages at lower applied bias voltages at lower $\frac{w}{\sqrt{w}}$ 100000 $\frac{w}{\sqrt{w}}$ average efficiency over the sensor that $\frac{w}{\sqrt{w}}$

larger than the timestamp precision obtained in each of the planes. The use of timing

 $\bullet\,$ No deterioration of the telescope performance has been observed to a rate of 5 MHz/cm². **6.5 High rate performance performance performance performance performance performance performance performance p**

Bias Voltage [V]

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0 200 400 600 800 1000 าเ ϵ kness,เm \mid 0 \overline{a} tested can be distinguished in three families, whose characteristics are summarised in table below. The sensors have been tested more than 30 different assemblies have been tested with beam with the aid of the Timepix3 telescope in order to assess the best candidate for the VELO upgrade. Two different manufacturers, Hamamatsu (HPK) and telescope in order to assess the sest candidate for the VEEO apgrade. Two amerent manaracturers, Flamaniatsa (in Ty and
Micron, provided sensors of different bulk types (n-on-p and n-on-n), thickness, implant width and gua d
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in $me{\textnormal{pix3}}$

> Charge collection with a Lands Gaussian. Sensors from all the families of prototypes meet the

HV tollerance Charge collection Efficiency

S22, 35 µm implant $\sum_{i=1}^{n}$ $\sum_{i=1}^n \sum_{j=1}^n \sum_{j=1}^n$ ron n-on-n

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\mathbf{r} ine at the pixel corners at lower applied bias voltages at which lead to a lower average efficiency over the sensor (Figure 10). Testbeam Results - EfÞciency • irradiated assemblies show inefficiencies at pixel corners at lower applied V, but are fully efficient at 1000 V S29: 150µm Micron, n-on-n, 450 µm inactive edge EfÞciency as a function of in-pixel position for **irradiated** sensors rance and Charge collection and Efficiency \mathcal{I} denote by \mathcal{I} and \mathcal{I} 05/09/2016 Emma Buchanan PIXEL 2016 18 $\frac{1}{2}$ after in two different readout modes, and analog and analog and analog and analog and analog and analog and an binary (Figure 11). In the analog mode the charge collected

between 100-110 V for HPK and less than 40 V for Micron

uniformly irradiated

assemblies.

AMERICA ACTS TO START THE START OF START corners voltage for uniformly irradiated at JSI. C FDNI \odot 0010 **Providige 101** annoning inducted **Sensor is shown as a function of plas voltage for sensors** Average efficiency over the sensor as a function of bias voltage for sensors $CLNN \otimes ZU10.$ S29: 150µm Micron, n-on-n, 450 µm inactive edge Average efficiency over the sensor as *D. Resolution* m UTHIY in aural cution α CERN © 2018. a function of bias voltage for sensors uniformly irradiated at JSI.

High rate

located upstream in the beam line. The maximum achievable sustained intensity is $26.26\pm2.26\pm2.2$

Resolution HPK n-on-p, 39µm implant, 450µm gr, JSI Full Fluence **NESURLIUII** HPK n-on-p, 39µm implant, 450µm gr, JSI Full Fluence HPK n-on-p, 39µm implant, 450µm gr, JSI Full Fluence 10 $\frac{1}{2}$ 10 10

 \mathbb{R}^2

specification at a bias between 700 and 800 V.

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electrons

MPV [

ne leakage current as a function of the bias voltage for sensors irradiated the bias voltage for sensors irradiated The plas voltage for sensors in adiated
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of -34°C. $CFIN \odot 2010$ charge distribution with a Landau function convoluted with a Charge Collection and Efficiency After Irradiation 86 30 30 30 30 30 30 30 **Sensor EDR - 31/05/2015 daniel.saunders@cern.ch 14/19** • Larger implant (S17, blue) T
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 $\frac{1}{2}$ Equation of $\frac{1}{2}$ \pm to full fluence at JSI. \mathbf{A} a function of the bias voltage for a u **corners** $\mathcal{L}_{\text{CKIN}} \otimes \mathcal{L}_{\text{ULO}}$ corners when it is increased with a landau function increased with a landau function of the concern
Convolution with a landau function with a landau function of the convolution of the convolution of the convolu **CERN © 2018.** -
current as a function of The Most Probable Value (MPV) of Average efficiency over th distribution is shown as a function of the bias voltage for the charge distribution is shown as sensors uniformly neutron irradiated *electrons*CERN © 2018. $\sum_{i=1}^n$ RI
a function of the bias voltage for as the fraction of tracks with an associated cluster on the set of ge for sensors irradiated the charge distribution is shown as a function of bias voltage lines that show lower leakage current) to full fluence at JSI.
and at full fluence at the temperature CERN © 2018.

MPV HPK 450^µ

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Figure 6: Predicted points resolution and uncertainty (solid blue curves) in the *CERN* © 2018. m
M e biased resolution from simulation and along the beam axis. The plink region band) as a function of the position m
(bl lue
| $\frac{1}{2}$ θ 60 $\frac{1}{2}$ ue
ue $\frac{1}{\sqrt{2}}$ angle for non-track angle for non-tradiced sensors (top) and uniformly neutron is $\frac{1}{\sqrt{2}}$ Predicted pointing resolution (blue along the beam axis. The pink region data are indicated by green and red markers, respectively [4].

- The simultaneous ToT and ToA measurements of the Timepix3 offers a fast, simple and robust pattern recognition and track reconstruction. In the simulteness of TeT and TeA first simulations for any in A measurements of the Timepix3 offers a fast. simple and robust reconstruction. only. The plane-to-plane variation does not depend on the rate and remains constant. \blacksquare The simultaneous for
- The use of a charge-weighted clustering algorithm and a track-based alignment procedure provide residuals of the order of $4 \mu m$ for each telescope plane. $\frac{1}{2}$ incluse or a charge weighted residuals and substanting in $\frac{1}{2}$ \blacksquare The use of a charge-weighted clustering algo from face tracks is estimated by performing a fit to the telescope
- \blacksquare The pointing resolution at the DUT position, in the centre of the telescope, is determined to be 1.69 ± 0.16 μ m. The puriting resolution at the DOT position, in the centre or the telescope, is determined to be \blacksquare The pointing resolution at the DUT position. $\frac{160+0.16 \text{ nm}}{20}$ $\frac{1}{2}$.07 = 0.10 μ
- A time resolution of 350 ps is achieved for reconstructed tracks traversing eight telescope planes. at incredition. Tecturistic recognition. The highest rates of about 6*.25 x 106 particles*

Left: Photograph of the Timepix3 telescope. CERN © 2018. Right: Mechanical design of the Timepix3 telescope, with the coordinate system displayed at the top. The telescope stations are mounted on two retractable arms around a central stage. The central stage is reserved for studies on DUTs; it provides translations in x and y as well as rotations about the y axis [4]. in *x* and *y* as well as rotations about the *y* axis.

kinematic/geometric s

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VELO functionality

- Detector surrounding the proton-proton interaction region
- **. Integrated in the LHC vacuum system** mitegrated in
- **EXTERF Halves retractable during the beam injection and setting**
- \blacksquare Excellent hit and geometry impact parameter resolution

ARD AND AND AND AND Spatial resolution $\frac{1}{2}$ is used by DUTs larger than the available space of less demanding in terms of $\frac{1}{2}$

a telescope plane [4].
CERN © 2018. The leakage current as a function of **of** $\frac{1}{2}$ $\frac{1}{2}$ $\frac{3}{2}$ Unbiased x residuals as a function of $\begin{array}{c} \begin{array}{|c|c|c|c|c|}\n\hline \begin{array}{|c|c|c|c|}\n\hline \begin$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{4}$ $\frac{1}{2}$ $\frac{1}{2}$ **CERN © 2018.**

ник n-on-p
HPK n-on-p

Micron n-on-p, $\frac{3}{50}$ Micron n-on-n, $\frac{3}{50}$ Micron n-on-n, \overline{a}

 $Micron-n-n-p$ $Micron-n-n$ Micron n-on-n, $\sqrt{36}$

HPK n-on-p

 HPK n-on-p

re collection

 $A-on-p$ $-on-p$ $A-on-p$ $m \cdot n$ -on-p, 360×1500 $m \cdot n - m$, 360 $m \cdot n$ $m \cdot m - n$

Teste beam Results - Effects -

Resolution in x direction as a function of the track angle for non irradiated sensors (1,2) and uniformly neutron irradiated senso st $\left| \frac{C}{2} \right|$ in analog (1.2) readout and binary (2.4) readout mode. CEDN @ 2010 τ , it can be induct. CLIN that \geq 2010. s ensors (1,2) and uniformly neutron irradiated sensor \mathbb{R}^2 \cdot non irradiated sensors (1,2) and uniformly neutron irradiated sens $\frac{1}{100}$ $\frac{1}{x}$ MPV [ke-] $\frac{1}{2}$.
مار d sensors (1,2) and uniformly neutron irradiated senso or non irradiated sensors (1,2) and uniformly neutron irradiated senso $\frac{1}{2}$ ad $\frac{1}{2}$ \geq $\frac{d}{dx}$ $\overline{}$ ⊖ensors (1,2) and uniformly neutron irradiated sensor:
⊳ $\overline{1}$ 20 20 80 80 −50 0 50 100 at JSI (3,4), in analog (1,3) readout and binary (2,4) readout mode. CERN © 2018. do
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- $\ddot{\mathbf{r}}$ Resolution in x direction as a function of the track angle for non irradiated sensors (1,2) and uniformly neutron irradiated sensors
at JSI (3,4), in analog (1,3) readout and binary (2,4) readout mode. CERN © 2018. ad
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| MPV [ke-] $u = \frac{1}{2}$ to the electric field must be electric field must be electric field must be electric field must be last pixel. Both effects can be attributed to different guard ring of the y position of the residual variation of the residual variation of the residual variation across the res
Set of the residual variation across the residual variation across the residual variation across the residual v

telescope, the charge can be studied as a function of the charge can be studied as a function of the charge can be studied as a function of the charge can be studied as a function of the charge can be studied as a functio

References annealing. This might be because of the lack of cooling during transport. Without $t_{\rm eff}$ telescope, the charge can be studied as a function of the charge can be studied as a function of the charge can be track position of the DUT. Figure 12 shows the DUT. Figure 12 shows the MPV of the MPV of the MPV of the MPV o charge distribution as a function of the distribution of the edge \mathcal{L}_1 Speedy PIxel Detector Readout (SPIDR) [6] board, specifically designed for the readout of Medipix3 and Timepix3 and Timepix3 and Timepix3 chips at Medipix3 chips at Timepix
3 chips at the readout of Medipix3 chips at the readout of Medipix3 chips at the readout of Medipix3 chips at

- [1] I. Bediaga et al., "Framework TDR for the LHCb Upgrade: Technical Design Report," Tech. Rep. CERN LHCC-2012-007. LHCb-TDR-12, Apr 2012. [Online]. Available: https://cds.cern.ch/ record/1443882 [1] I. Bediaga et al., "Framework TDR for the LHCb Upgrade: Technical Design Report," Tech
CERN LHCC-2012-007. LHCb-TDR-12. Apr 2012. [Online]. Available: https://cds.cern.ch $\begin{bmatrix} 1 \\ 1 \end{bmatrix}$ Dedisco stel "Exemplical TDD for the pixel of $\begin{bmatrix} 1 \end{bmatrix}$ is bedding to dat, the direction pixels. The definition of the border between pixels. The definition of the border between pixels. The definition of the border between pixels. The definition of the border C_{Edd} is to collect contract conditions that $\frac{1}{2}$ ICh Ungrade: Technical Design Penert" Tech Pen performation definition depth measurements and international depth measurements and increasing and international in
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12-007. LHCb-TDR-12, Apr 2012. [Online]. Available: https://cds.cern.ch/
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[2] LHCb Collaboration, "LHCb VELO Upgrade Technical Design Report," Tech. Rep. CERN LHCC-2013- $\mathsf{S}\mathsf{S}\mathsf{S}\mathsf{S}\mathsf{S}$ and $\mathsf{O}21$. LHCB-TDR-013, Nov 2013. [Online]. Available: https://cds.cern.ch/record/1624070 Z ring consideration. Linux velocity \overline{z} \overline{a} depth. The gradie technique consistent \overline{a} sensor almost parallel (83-89 degrees) to the beam of the beam of
- DELLER DELLE
[3] T. Poikela et al., "VeloPix: the pixel ASIC for the LHCb upgrade," JINST, vol. 10, no. 01, p. C01057, 2015. in the last pixel column from traversing the guard ring traversion of α

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120 140 \mathbf{h} leakage Current Curren **Micro**n Co 21 M.I.C -2 1 MeV neq cm ¹⁵ HPK n-on-p, IRRAD <10 over the entire pixel cell. Assemblies irradiated at full fluence meet the efficiency requirement at 1000 V, but start to show \mathbf{r} inefficiencies at the pixel corners at lower applied bias voltages which lead to a lower average efficiency over the sensor over the sensor over the sensor over the sensor over (Figure 10). **Irradiated Results - Voltage scan** Testian Results - Effective EfÞciency as a function of in-pixel position for **irradiated** sensors EfÞciency as a function of in-pixel position for **irradiated** sensors $\mathbf{r} = \mathbf{r} \cdot \mathbf{r}$ assemblies are fully efficient over the entire pixel cell • irradiated assemblies show inefficiencies at pixel corners at lower applied V, but are fully efficient at 1000 V *Number of tracks / chip / bunch crossing.* Fig. 2. Mean number of particles crossing an ASIC per bunch crossing. The

−50 0 50 100

−50 0 50 100

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charge is lost from the last pixel to the guard ring area. After

zo 15.
[4] Kazu Akiba, et al. "LHCb VELO Timepix3 Telescope", arXiv:1902.09755 [physics.ins-det] −50 pm = 50 nm = 50 n −50 0 50 100 −50 0 50 100 −50 0 50 100 −50 50 1000 5 −50 0 50 100 r resolution. The prototype sensors have different guard ring guard ring $\frac{1}{2}$

VIII International Course "Detectors and Electronics for High Energy Physics, Astrophysics, Space and Medical Physics" rates, the configuration of the Timepix3 telescope was altered with respect to the one charge distribution as a function of the distance from the edge of the pixel matrix for the three formulations of the three families of sensors understand the three families o investigation. The solid line represents the edge of the pixel ℓ

VeloPix: the pixel ASIC. CERN © 2018.

Pixel detector^[2]

- Better/more robust pattern recognition and alignment performance (compared to strips)
- Improved spatial and impact parameter resolution
- Closer to beam $(8.1 \rightarrow 5.1)$ mm
- Approx. 10 times more fluence than the current design ~10¹⁶ n_{eq}/cm²

High rate

Fraction of clusters non assiciated to tracks as a function of the particle rate for the telescope planes [4]. CERN © 2018

Pointing resolution