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Investigation of crosstalk effects in RD53A modules with 100 and 150 μm thick n-in-p planar sensors

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The CMS and ATLAS detectors will face challenging conditions after the upgrade of the LHC to the High Luminosity LHC. In particular, the granularity of the pixel detectors should increase to mitigate the effect of pileup. Two possible sensor geometries are being investigated, $50 \times 50\ \mu m^2$ and $25 \times 100\ \mu m^2$, to handle these conditions. One of the main factors in choosing the pixel geometry is inter-channel charge induction or crosstalk, defined as the ratio of charge induced into neighboring pixels relative to the total charge. This charge induction will affect the data rates, position resolution, and track reconstruction efficiencies. Therefore, it should be investigated carefully. The effect of crosstalk is expected to depend on the chosen pixel geometry, threshold of the signal, and readout front-end. The readout chip in this study is RD53A, developed by the RD53 Collaboration, which is a prototype investigated by both the CMS and ATLAS collaborations implementing three different analog front-end designs. Crosstalk effects are larger for the $25 \times 100\ \mu m^2$ geometry, given the larger sensor capacitance. Both have been studied in the lab through direct charge injection, and also at DESY test beam facility by charge deposition of 5.6 GeV electrons in 150 μm thick silicon pixels. The effects on the cross-talk due to varying the front-end, threshold, and the impinging position of the electrons will be presented.

European Physical Society Conference on High Energy Physics - EPS-HEP2019 - 10-17 July, 2019
Ghent, Belgium

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PoS(EPS-HEP2019)151

1. Introduction

After the upgrade of LHC to High Luminosity LHC (HL-LHC), the high level of pileup will introduce complications for the detectors taking data from the HL-LHC proton collisions. The CMS and ATLAS collaborations are planning to increase the granularity of their tracking layers to mitigate the effect of pileup. The RD53A readout chip [1], developed by the RD53 collaboration for these pixel detectors, has a geometry of 50×50 μm^2 and therefore, two geometries of 50×50 μm^2 and 25×100 μm^2 are being studied for the sensors. In the geometry with a 25×100 μm^2 cell size, the layout of the aluminum pad, overlaying the neighboring implant, can cause inter-channel charge induction or crosstalk between the pixels paired by these pads (Figure 1). The crosstalk effect is more pronounced between these pairs, but a small amount of charge can also be induced in other neighboring channels. Crosstalk causes two main complications. It increases the number of pixels with an over-threshold charge, which leads to higher data-rates, and it increases the error on cluster position reconstruction, and subsequently track reconstruction.

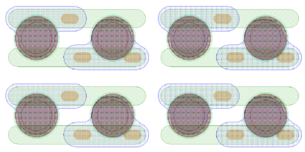

Figure 1: Aluminum pads (blue) are needed to establish an electrical contact and transfer the charge from the pixel implant (green) with a 25×100 μm^2 pitch to the Under-Bump-Metallization pad (dark gray circle) with a 50×50 μm^2 pitch. The pad of one cell overlays the neighboring implant, increasing the total input capacitance.

The crosstalk has been measured with two different methods in this study. The first one consists of a self-injection in the readout chip for a single pixel or a group of pixels together with the subsequent analysis of the occupancy of the neighbouring pixels. The second method utilizes the charge deposition of particle beams in the silicon pixels while investigating the charge sharing distribution for paired and unpaired pixels.

2. Measurements by direct charge injection

Crosstalk can be studied by direct charge injection in specific channels of the RD53A chip utilizing the BDAQ53 software [2] and a corresponding firmware programmed on a Kintex-7 FPGA. A global threshold can be set per front-end and, in addition, the threshold can be fine-tuned per pixel in the linear and differential front-ends, with a 4- and 5-bit DAC, respectively. Increasing charges can be injected in one RD53A channel. For each charge, it would be injected 100 times into each pixel to obtain the mean occupancy. The obtained data is fitted with an error function (S-curve) from which the point corresponding to 50% occupancy is taken as the channel threshold. In Figure 2, a superposition of S-curves of all the pixels of the linear front-end for an RD53A module with non-irradiated 150 μm thick MPG-HLL sensors [3] of 25×100 μm^2 pitch is shown. The mean threshold is at 987 electrons.

If, instead, we inject charge into a channel but count the occupancy of its paired channel, the injected charge multiplied by the crosstalk value (induced charge) should be above the threshold

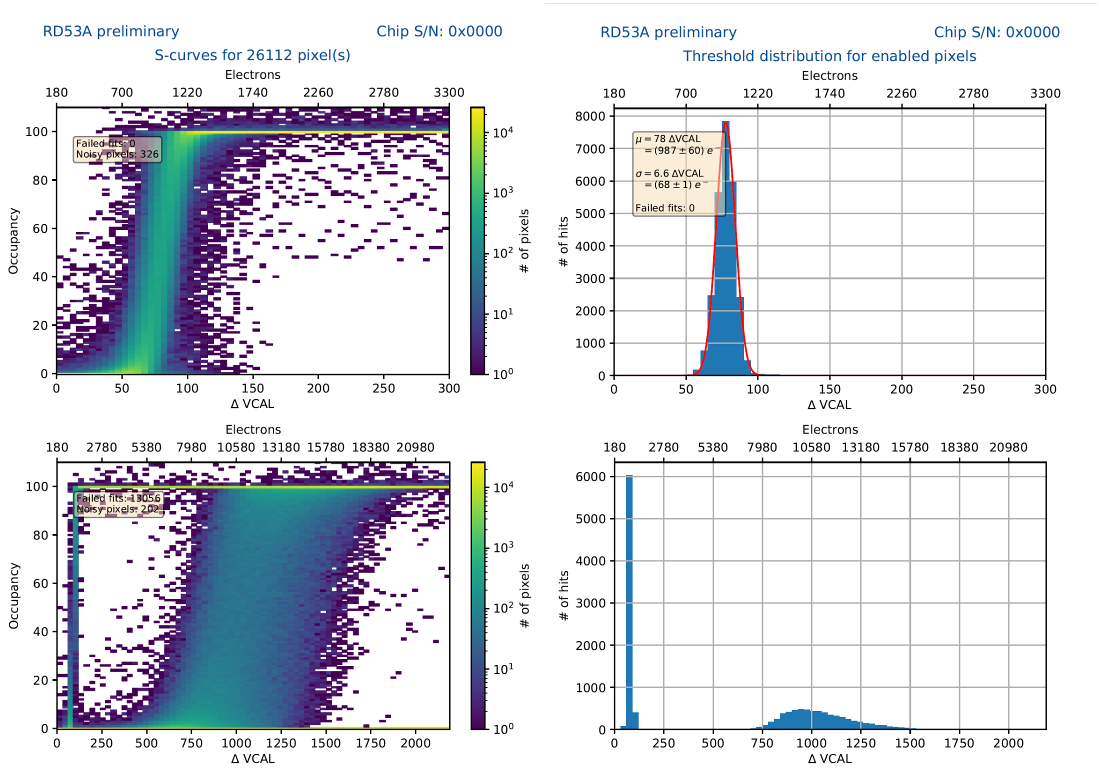

Figure 2: Occupancy vs injected charge or S-curves, measured for the linear FE when reading only the injected pixel (top left) and when injecting in one channel and reading both the injected channel and its neighbour (bottom left). The plots on the right show the respective threshold distributions.

of the paired channel to be recorded. The injected charge corresponding to 50% occupancy of the paired channel is defined as the crosstalk threshold.

$$\text{crosstalk} = \frac{\text{induced charge}}{\text{total charge}} = \frac{\text{S-curve threshold of injected channel}}{\text{S-curve threshold of paired channel}}$$

The S-curve obtained by injecting in one channel and reading the occupancy of both the injected channel and the paired one is also shown in Figure 2. Please note that in the linear FE the results are different if we read both the injected channel and its paired one, or read just the paired one. To be close to the operational conditions in which all the channels are ready to be read out, we present the values obtained when reading both the injected and paired channels.

These measurements were also performed on an RD53A module with 150 μm thick MPG-HLL sensors of $25 \times 100\ \mu m^2$ pitch, irradiated by CERN PS 24 GeV proton beam at $5 \times 10^{15} n_{eq}/\text{cm}^2$ fluence. The measured crosstalk values through direct charge injection in the lab for both irradiated and non-irradiated modules are presented in Table 1.

3. Measurements with electron beam

RD53A modules with HLL sensors of 100 and 150 μm thickness and $25 \times 100\ \mu m^2$ pitch were investigated with a 5.6 GeV electron beam to look for possible crosstalk effects. Synchronous, linear, and differential front-ends were studied. The synchronous front-end was tuned to the threshold

Crosstalk	linear	differential
non-irradiated	9.5% (7-12)	13.3% (11-18)
irradiated	7% (6-9)	12.5% (11.5-14.5)

Table 1: Crosstalk values for linear and differential front-ends of irradiated and non-irradiated RD53A modules, measured by direct charge injection. Parentheses indicate the range of measured crosstalk in different pixels.

of 770 electrons while linear and differential to 850 electrons. To measure the value of crosstalk, only the clusters with two pixels were studied. Charge sharing between these two pixels is in principle a combination of two effects. First, the impinged particle can deposit charge in both pixels with a ratio depending on the impinging point. Also, if the two pixels are affected by crosstalk, even if there is no normal charge sharing, a fraction of the deposited charge would be induced in the paired pixel. So, if the ratio of the charge in the pixel with lower charge to the total charge is taken, a rather flat distribution due to normal charge sharing is expected with a relatively sharp peak added on top, corresponding to the crosstalk value. Moreover, when the two pixels are unpaired, this sharp peak is expected not to be present. The distributions for paired, unpaired, and all clusters with two pixels for the three front-ends are shown in Figure 3. Results are similar for the module with 100 μm thick sensors.

As an illustrative example, the results from studying the linear front-end of the module with 150 μm thick sensors are shown in Figure 4. Analyzing the ratio between the number of clusters with two hits over those with one, we observe that the crosstalk effect is mitigated for higher thresholds (4a). Due to the crosstalk effect, the uncertainty on the cluster position resolution, measured from the residual distribution is higher for paired channels than unpaired ones (4b).

4. Conclusion

The inter-channel charge induction in the RD53A modules, known as crosstalk, is measured in two ways. First, in the lab by studying the induced charge in a neighboring pixel due to direct charge injection in a pixel. Second, using an electron beam and studying the charge sharing distribution of size-two clusters. Measured values are largely consistent between the irradiated and non-irradiated modules and between the lab measurements and test beam results. The crosstalk in the irradiated modules is lower, which is expected due to charge trapping and lower average charge per pixel, which leads to induced charges that are under the required threshold in the neighboring pixels.

References

[1] The RD53A Integrated Circuit, `https://cds.cern.ch/record/2287593?ln=en`

[2] BDAQ Software and Hardware, `https://gitlab.cern.ch/silab/bdaq53`

[3] J. Beyer "Optimization of pixel modules for the ATLAS inner tracker at the high-luminosity LHC", Ph.D. Thesis, LMU Munich. `https://edoc.ub.uni-muenchen.de/23939/`

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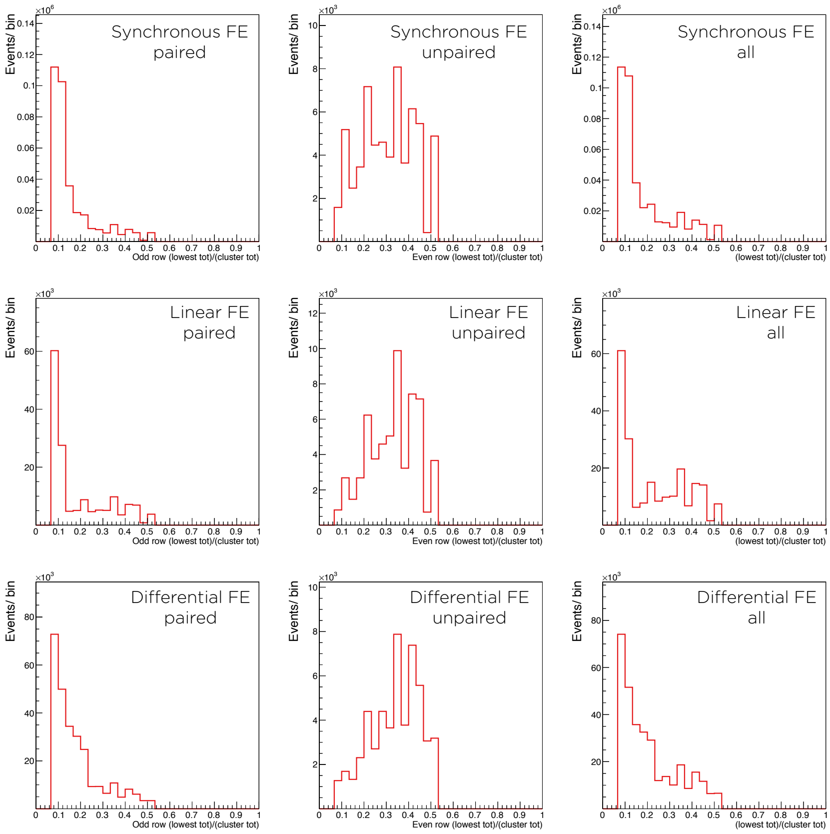
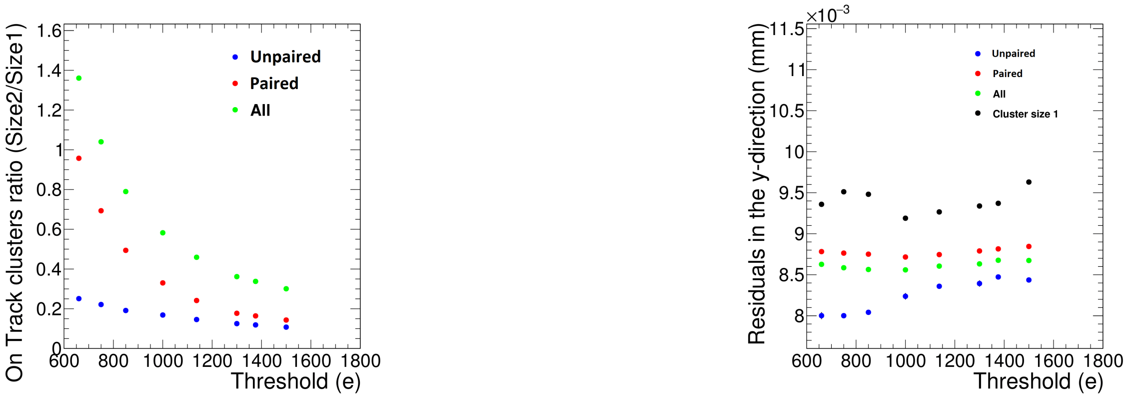


Figure 3: Distributions of the ratios of the lower charge in a size-2 cluster over the total charge. The plots on the left show this distribution for size-2 clusters with paired pixels only, the ones in the middle for clusters with unpaired pixels, and the ones on the right inclusively for all size-2 clusters.



(a) Ratio of number of size-2 clusters over single pixel clusters.

(b) Residual distribution.

Figure 4: Effect of threshold on cluster size and residual distribution of the reconstructed position of the clusters compared to the more precise positions obtained by track reconstruction using additional tracking layers, analyzed for paired pixels, unpaired pixels, and for all pixels together.