Development of CMOS pixel sensors for the ALICE ITS upgrade

PICSEL group

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ALICE Inner Tracking System upgrade

ALICE is a general purpose experiment dedicated to the study of nucleus-nucleus collisions at LHC. After more than 3 years of successful operation, an upgrade of the apparatus during the second long shutdown of LHC (LS2) in 2017/18 is under study [1]. One of the major goals of the proposed upgrade is to extend the physics reach of the experiment for rare probes at low transverse momentum.

This target will be achieved thanks to the two important improvements. The first one is the increased luminosity of the LHC in Pb-Pb collisions after the LS2 reaching $\mathscr{L} = 6 \times 10^{27}$ cm^2s^{-1}. The second one is an upgrade of the main tracking detectors at central rapidity.

Upgrade of the Inner Tracking System (ITS) is an important part of this project. Indeed, the main purpose of the ITS is to improve the primary vertex position and to reconstruct the decay vertices of heavy flavor particles. An improvement of the spatial resolution of the ITS by increasing the segmentation and decreasing the material budget will allow to extend the accessible transverse momentum range well below the current limit of $p_T \approx 2$ GeV/c.

The new ITS will have to cope with the important event rates of 50 kHz in Pb-Pb collisions and several hundreds of kHz in pp collisions. These elevated event rates will lead to a relatively high radiation load on the detector. According to recent simulations, the overall dose expected for the full physics program after LS2 for the innermost layer can reach up to 700 kRad and 10^{13} n_{eq}/cm^2 including a safety factor of 4.

Conceptual upgrade design

A conceptual design of the new ITS [2] includes 7 layers of pixel detectors. Optionally the 4 outermost layers can be equipped with the silicon micro-strip detectors. The parameters of the proposed layout are summarized in Table 1. The performance of the new layout in terms of the pointing resolution, p_T-resolution and tracking efficiency was evaluated via numerical simulations. The expected pointing resolution of the new detector is compared with that of the present ITS in Figure 1. It is clear that the upgrade of the ITS can significantly improve the performance of the detector. For example, the pointing resolution in rφ plane becomes 3 times better at 1 GeV/c, passing from about 60 μm to ≈ 20 μm.

Table 1: Parameters of the conceptual layout of the ITS upgrade. Numbers in parentheses correspond to the micro-strip detectors.

Layer	Type	R [cm]	±z [cm]	Intrinsic resolution [μm] rφ	Intrinsic resolution [μm] z	Material budget [% X_0]
	Beam pipe	2.0	-	-	-	0.22
1		2.2	11.2	4	4	0.3
2	Pixels	2.8	12.1	4	4	0.3
3		3.6	13.4	4	4	0.3
4		20.0	39.0	4 (20)	4 (830)	0.3 (0.83)
5	Pixels (Strips)	22.0	41.8	4 (20)	4 (830)	0.3 (0.83)
6		41.0	71.2	4 (20)	4 (830)	0.3 (0.83)
7		43.0	74.3	4 (20)	4 (830)	0.3 (0.83)

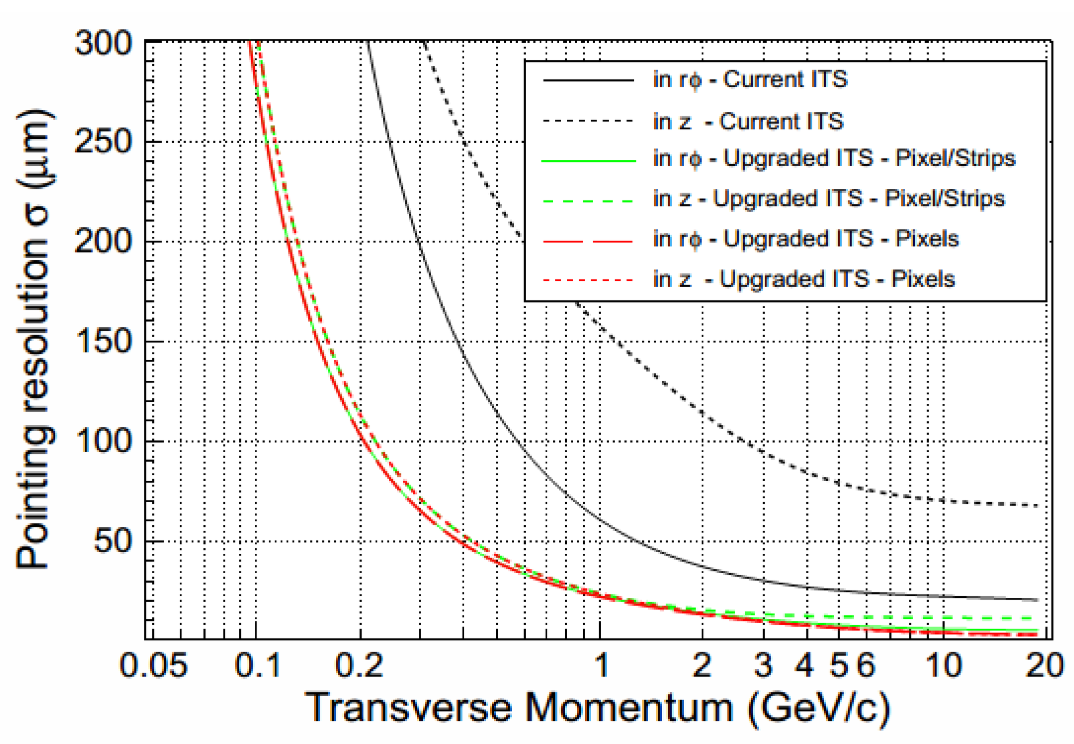

Figure 1: Pointing resolution to the vertex for charged pions as a function of the p_T for the current and the upgraded ITS.

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CMOS Pixel Sensors technology

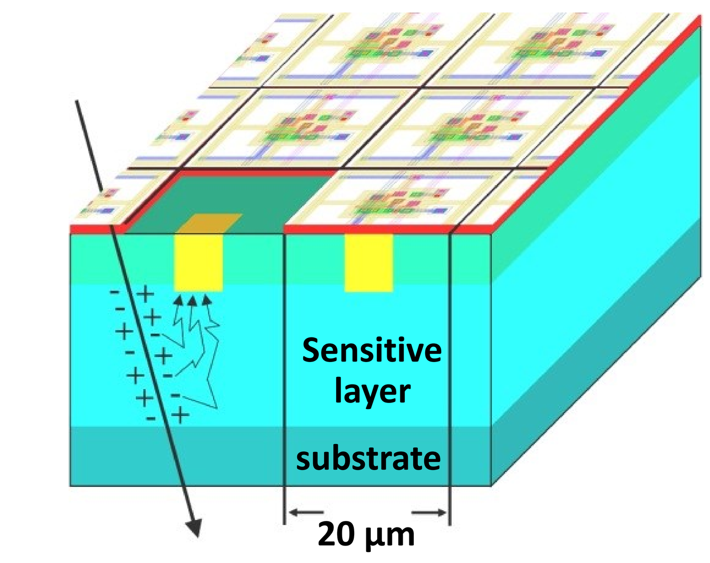

Figure 2: Schematic cross-section view of a CMOS pixel sensor

Significant performance improvement of the ITS will become possible by the use the CMOS pixel sensors (CPS). These sensors are implemented in a single silicon die where the signal is generated in the thin epitaxial layer located beneath the readout electronics layer. The schematic structure of a CPS is shown on Figure 2. Such close integration first of all gives a possibility to significantly reduce the pixel pitch to about 20 μm. Moreover, by thinning the chip to ~50 μm an overall material budget of ~ 0.3 % X_0 per layer can be envisaged.

The radiation hardness of CMOS sensors was initially limiting their application in high energy physics experiments. However, the radiation tolerance of the CMOS chips is being improved thanks to the recent developments of the commercial CMOS production. Presently the STAR collaboration is installing PXL[3], the first tracking system in a subatomic physics experiment based on CMOS sensors. It is equipped with 400 *Ultimate* chips developed by the PICSEL group and produced in *AMS* 0.35 μm CMOS process. These chips can withstand the combined dose of 150 kRad and 3×10^{12} n_{eq}/cm^2 at the operation temperature of 30° C.

Nevertheless, in order to satisfy the more demanding requirements of the ITS upgrade, another CMOS process with a reduced feature size had to be explored.

Radiation hardness of the *TowerJazz* 0.18 μm CMOS process

In December 2011 a first prototype chip, MIMOSA 32, was designed at IPHC, in collaboration with IRFU (Saclay), in order to study the radiation hardness of the *TowerJazz* 0.18 μm CMOS imaging sensor (CIS) process. After the return from the foundry in March 2012 the chip was extensively tested in the laboratory at IPHC and with MIPs at the CERN-SPS. Various performance parameters, like charge collection efficiency (CCE), noise, signal-to-noise ratio (SNR), particle detection efficiency and single point resolution, were measured for the non-irradiated chips and for the chips irradiated with different doses of ionizing and non-ionizing radiation.

Before irradiation the SNR of the seed pixel of the cluster amounted to about 30. After irradiation with the combined dose of 1 MRad and 10^{13} n_{eq}/cm^2 the SNR was measured in the range from 22 to 16, depending on the temperature, as can be seen in Figure 3. These SNR values resulted in particle detection efficiency better than 99% at 30° C [4].

These results provide evidence for the adequacy of the *TowerJazz* 0.18 μm CMOS process to the requirements of the ALICE ITS upgrade project.

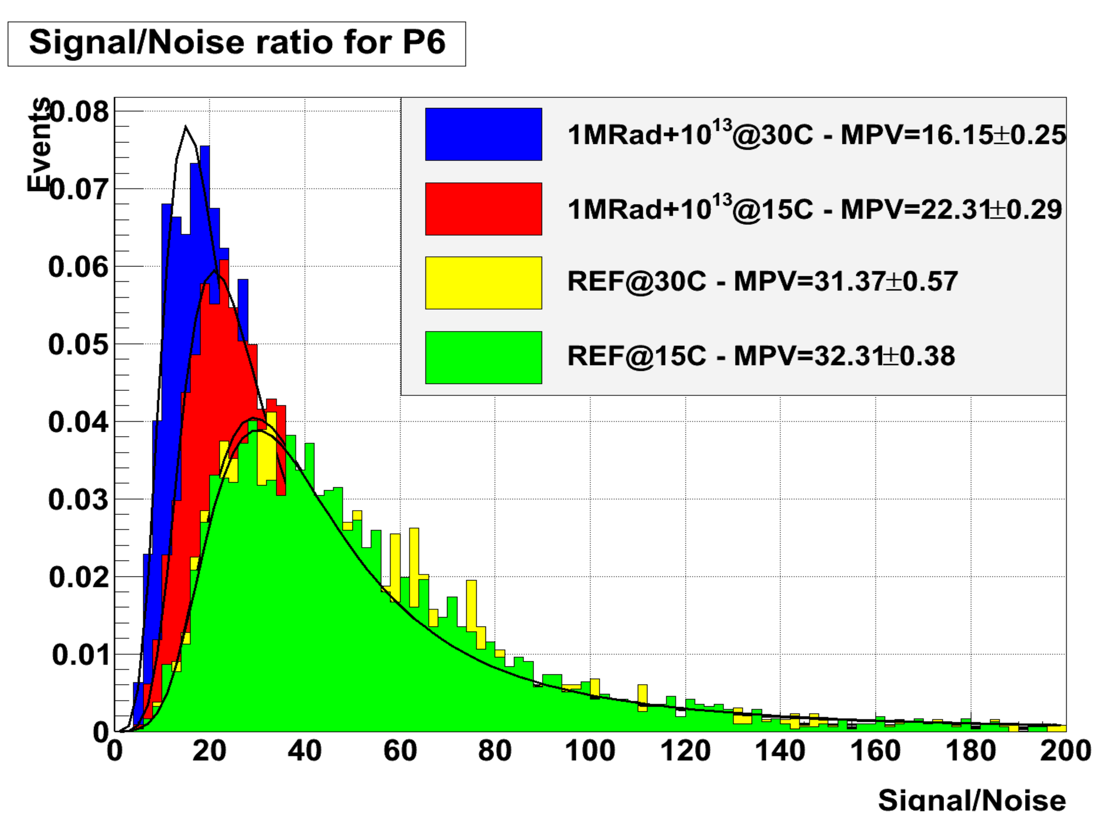

Figure 3: Signal-to-noise ratio distributions for cluster seed pixels composing the submatrix with square pixels of 20 × 20 μm² at 15° C and 30° C, before and after irradiation with the combined dose of 1 MRad and 10^{13} n_{eq} /cm².

Final chip development

The final design of the CPS for the ITS upgrade is currently in preparation by the three groups in IPHC (Strasbourg), CERN (Geneva) and RAL (UK). The main challenge of this development is to satisfy the conflicting requirements in terms of the spatial resolution, readout speed and power consumption.

The PICSEL group at IPHC is working on the two designs partially inheriting the architecture from the previous *MIMOSA* chips. Both chips with the pixel size of ~22×33 μm² will be read out in the column-parallel rolling shutter mode.

The first chip, called *MISTRAL*, will be equipped with column level discriminators. Reading two lines simultaneously will allow for a full matrix readout time of about 30 μs. The expected power consumption of the *MISTRAL* chip is below 350 mW/cm². The second chip, called *ASTRAL,* features a more advanced and sophisticated architecture. Based on in-pixel discriminators, the chip is expected to be read out in about 15 μs. The power consumption was estimated to be less than 200 mW/cm².

Developing CMOS sensors requires multiple prototyping steps in order to validate the different building blocks of the chip. In March 2013, the PICSEL group submitted several prototype chips as a part of the TowerJazz engineering run in collaboration with the CERN and RAL groups. Figure 3 shows the composition of the reticle submitted to the foundry. The production is expected to be completed by the end of May. Test results of the new chips will be included in the Technical Design Report to be submitted to LHCC by the end of August 2013. The next step will be the fabrication of a 1×1 cm² chip featuring the full readout chain, planned for 2014.

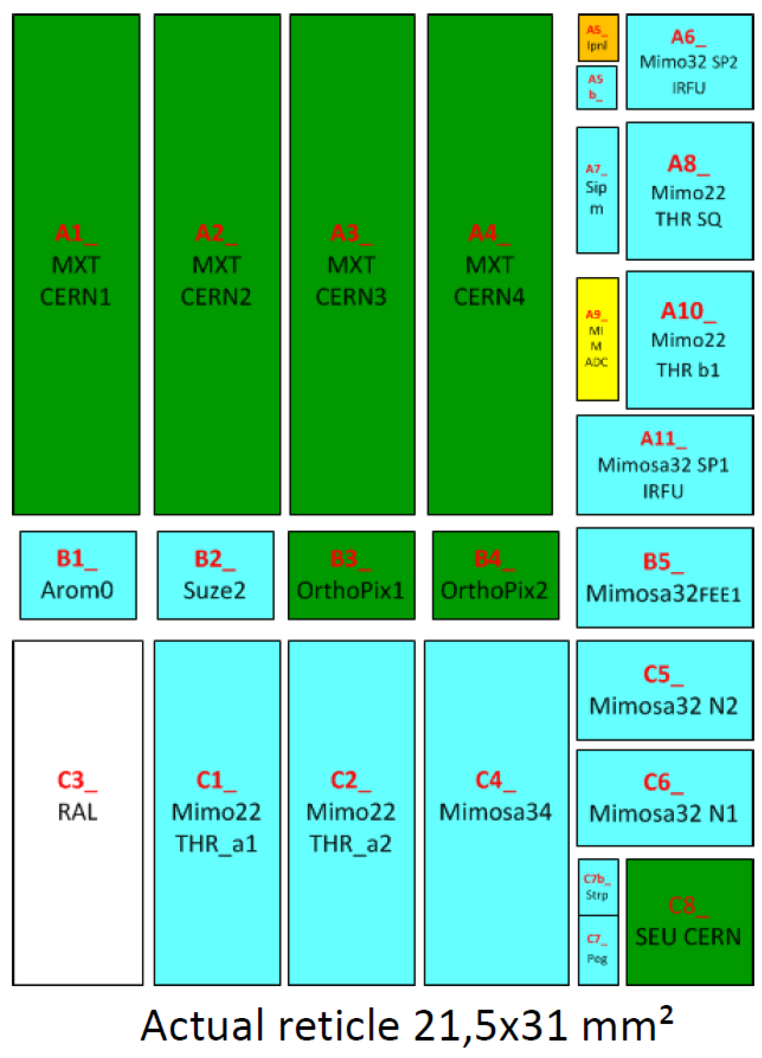

Figure 3: The composition of the reticle submitted to the TowerJazz for the engineering run in March 2013.

Conclusions

A new upgraded ITS is expected to significantly improve the physics performance of the ALICE detector in reconstruction of rare probes at low transverse momentum. This improvement will be obtained by relying on CPS providing the required high granularity and low material budget.

The radiation hardness of the *TowerJazz* 0.18 μm CMOS process has been recently found to satisfy the requirements of the ITS upgrade program.

The PICSEL group is presently pursuing the intensive R&D program towards the final design of the detector by 2015.

References

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