First Results on 3D Pixel Sensors Interconnected to RD53A Readout Chip after Irradiation to $1x10^{16}$ n_{eq}/cm^2

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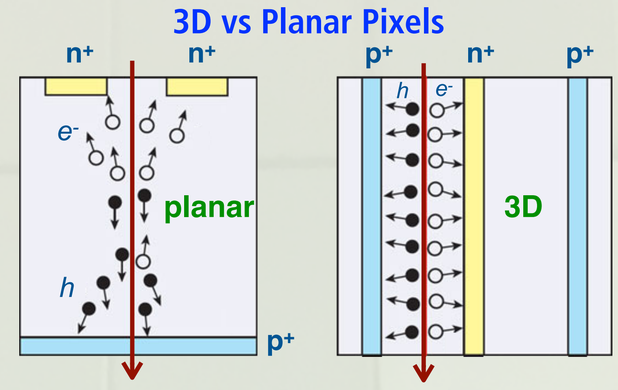
Pixel detectors in the innermost layers of the future HL-LHC experiments at CERN (Geneva, Switzerland) will have to survive with high tracking efficiency up to a **fluence** in excess of **$2x10^{16}$ neq/cm²**, while preserving high tracking efficiency. The total active sensor thickness should be small enough to keep both the bias voltage and the power dissipation after irradiation to a manageable level, but at the same time allowing for a reasonable amount of collected charge to reach full hit efficiency and good spatial resolution.

Why 3D pixel?

3D pixels, satisfying all of the above requirements, are very good candidates for the upgrade of Inner Trackers

3D vs Planar Pixels



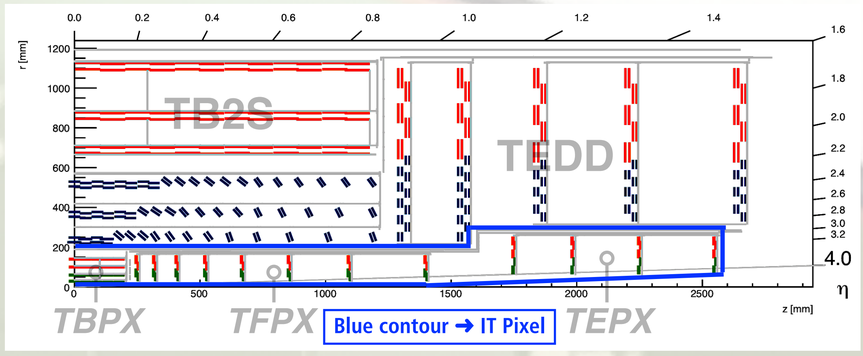
For the same sensor pitch and 150µm thickness, a traversing ionising particle creates the same number of electron-hole pairs but the max distance they have to travel before being collected is reduced from 150µm in planar to about 51µm (for 25µm x 100µm pitch 1E), 35µm (for 50µm x 50µm pitch) or down to 28µm (for 25µm x 100µm pitch 2E) in 3D pixels

➜ **Full depletion at lower bias voltage**, especially after heavy irradiation

➜ **Less trapping, higher collected charge**

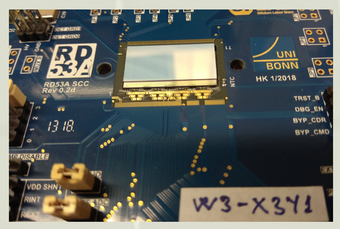
Layout of the proposed CMS Tracker at HL-LHC

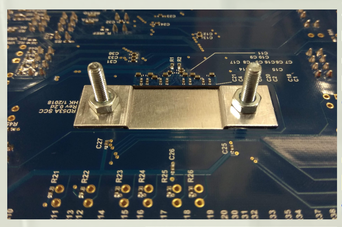
Inner Tracker (**IT**): 4.9m², 2G pixels; innovative **tilted geometry** in the inner barrel. **Outer Tracker** (**OT**): strip/strip (2S) and strip/macro-pixel (PS) modules, 13296 in total, 192m2, 42M strips, 170M macro-pixels (25m2).



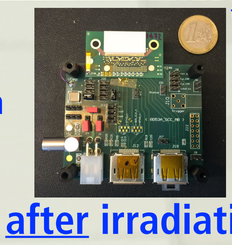
Module Construction and Test Beam

Pixel sensors were bump-bonded with RD53A prototype chips[2] in units with 76800 single pixel cells (400 rows, 192 columns), of overall dimension 20.0mm by 11.8mm, for simplicity called "modules". We tested 25µm x 100µm and 50µm x 50µm pitch modules on 120 GeV proton beam both before and after irradiation. Preliminary results presented here were obtained with the Linear Front-End of RD53A (136 columns, from 128 to 263).





3D module mounted on single chip "Bonn" card before irradiation. The card has a "hole" under the chip and an Al bridge shaped plate for support and thermal contact

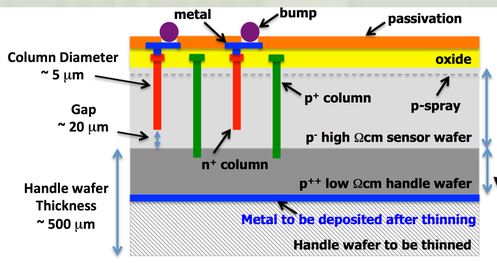


CMS Irradiation Card connected to readout adapter interface, both developed by RICE University

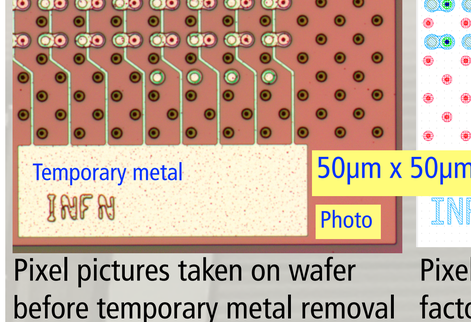
The dose for irradiated modules has been estimated to be about 6 MGy

The 3D Columnar Pixel Sensors

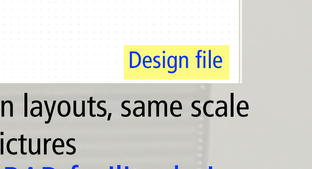
The 3D sensors[1] are fabricated in FBK foundry in Trento; they are developed in a joint collaboration program with INFN (Istituto Nazionale di Fisica Nucleare, Italy). The substrates selected for the 3D sensors are p-type Si-Si Direct Wafer Bond (DWB) or SOI (Silicon On Insulator). Handle wafer is 500µm thick low resistivity Czochralski (CZ). FBK active devices are implanted on Float Zone (FZ), high resistivity (>3000 Ohm cm), 130µm thick wafer.



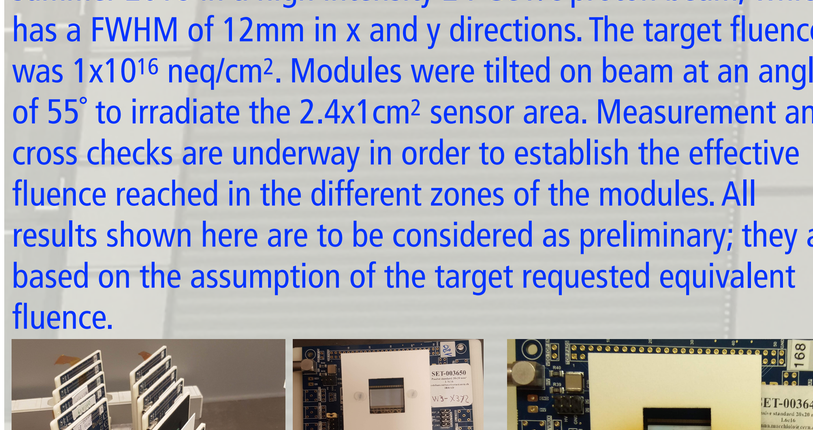
Artist's view of a 3D Pixel sensor (FBK). Columns are etched from top side only. CZ backside can be thinned down to be about 50µm thick

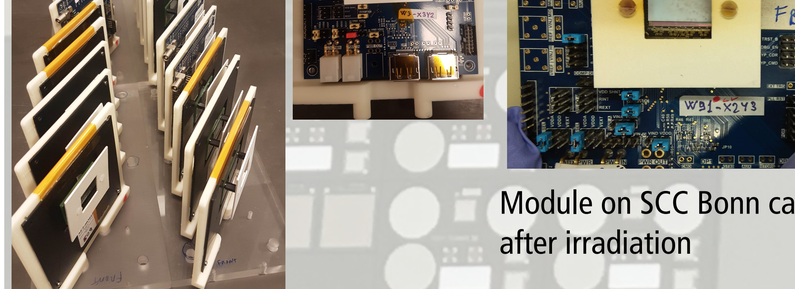


SEM pictures of Ohmic columns made by Deep Reactive Ion Etching (DRIE) in SOI wafer



Different pixels are implemented in the same wafer layout: 25µm x 100µm with two junction Electrodes (2E), 25µm x 100µm 1E, 50µm x 50µm





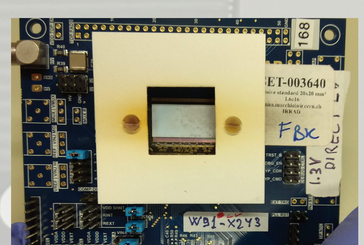
Pixel pictures taken on wafer before temporary metal removal

Pixel design layouts, same scale factor as pictures

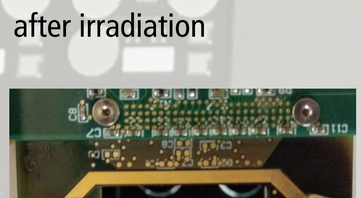
Irradiations were performed at CERN IRRAD facility during summer 2018 in a high intensity 24 GeV/c proton beam, which has a FWHM of 12mm in x and y directions. The target fluence was $1x10^{16}$ neq/cm². Modules were tilted on beam at an angle of 55° to irradiate the 2.4x1cm² sensor area. Measurement and cross checks are underway in order to establish the effective fluence reached in the different zones of the modules. All results shown here are to be considered as preliminary; they are based on the assumption of the target requested equivalent fluence.

Modules mounted on the tilted supports before installation in IRRAD.

Visual inspections after irradiation and data analysis confirm the irradiation on the modules was less uniform than expected.

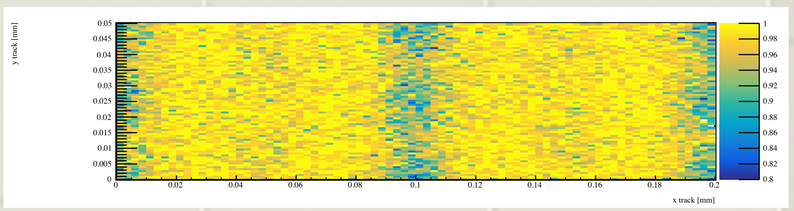


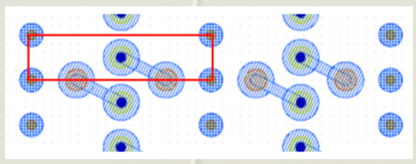
Module on SCC Bonn card after irradiation



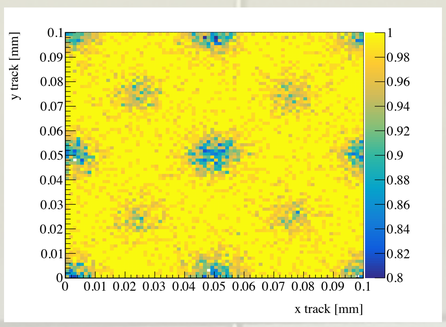
Module on RICE card after irradiation

3D Hit Efficiency before Irradiation

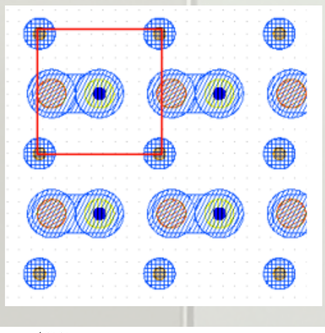


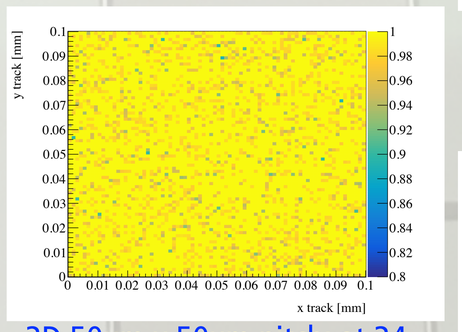


3D 1E 25µm x 100µm pitch, 0 deg tilt angle,
Efficiency 97.3% @ HV=3 V
Depletion voltage measured on planar test structure diode diode C-V characteristic is about 20 V for the whole 3D batch

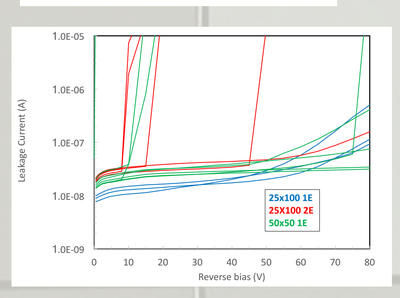


3D 50µm x 50µm pitch, 0 deg tilt angle,
Efficiency 98.6% @ HV=15 V



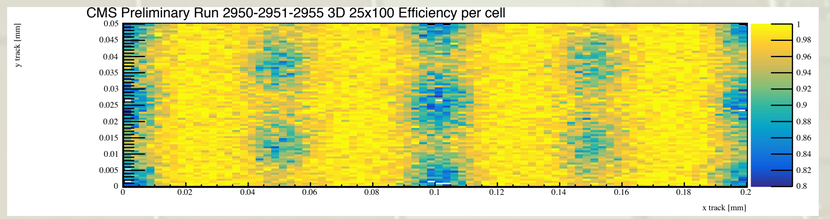


3D 50µm x 50µm pitch: at 34 deg tilt angle, geometrical inefficiencies are recovered
Efficiency 99.3% @ HV=35 V



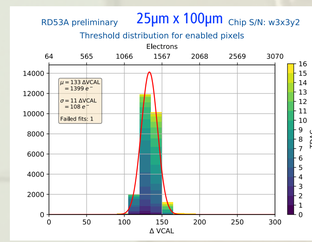
I-V Curves of 3D sensors measured on wafer using the temporary metal layer

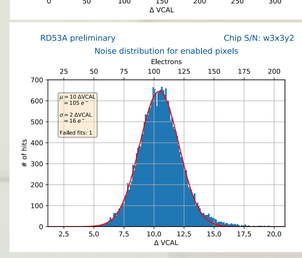
3D Hit Efficiency after irradiation

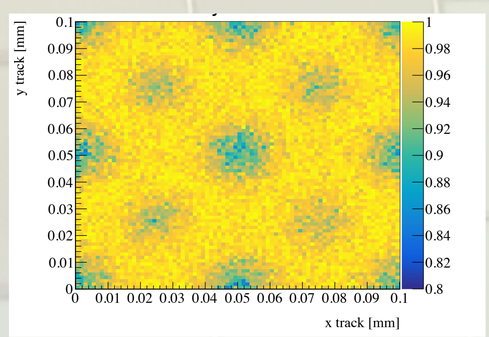


3D 1E 25µm x 100µm pitch, 0 deg tilt angle, **Efficiency 96.6% @ HV=120 V**

Threshold ~1400 e-, noise = 105 e-

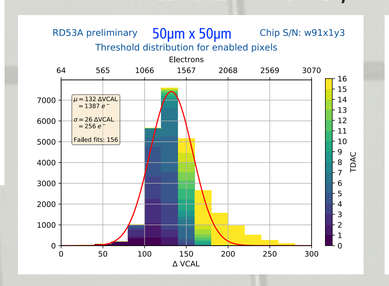


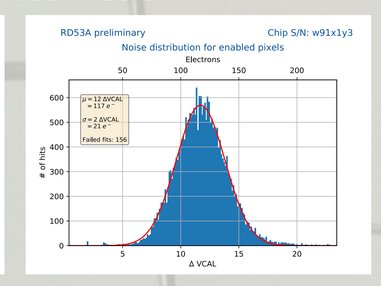


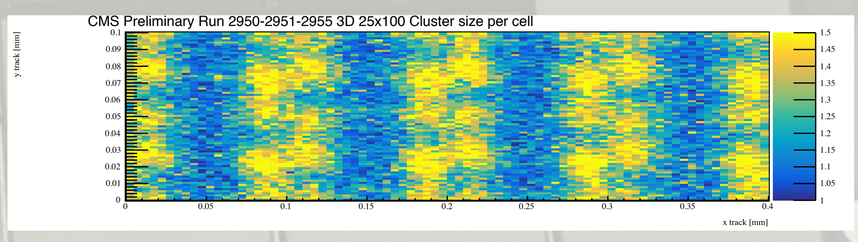


3D 1E 50µm x 50µm pitch, 0 deg tilt angle, **Efficiency 97.5% @ HV=150 V**

Threshold ~1400 e-, noise = 120 e-







Cluster size distribution of 25µm x 100µm pixel sensor, after irradiation. Projection on 4x4 pixel cell histogram

Hit Efficiency Summary Table

3D Pixel-RD53A	25µm x 100µm (0 deg tilt)	50µm x 50µm (0 deg tilt)
Before irradiation	97.3	98.6
After irradiation	96.6	97.5

Conclusions

Preliminary Test Beam results obtained with 3D pixel sensors show high hit efficiency both before and after irradiation at bias voltages below 200V. The same modules presented in this paper will be tested again in the Fermilab Test Beam Facility, possibly trying higher bias voltages and also RD53A analog front-ends other than Linear. New irradiations are already planned and will be done as soon as more RD53A chips will be available to build new modules. A new 3D sensors batch is in progress at FBK using Stepper process, mainly aiming at 3D sensor type 2E with 25µm x 100µm pitch.

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We thank RD53 Collaboration for the RD53A chip; we remind our results are not on chip performance but on sensor performance.

We thank Bonn ATLAS group for SCC cards and support for flip-chipping

References:
1) *Small pitch 3D devices, G.F. Dalla Betta, PoS Vertex2016 (2017) 028*
2) *The RD53A Integrated Circuit, Garcia-Sciveres, Maurice - CERN-RD53-PUB-17-001*

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