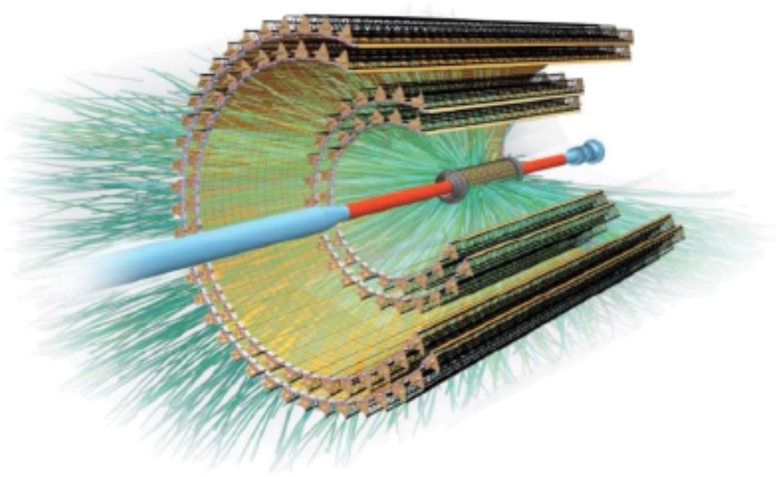
A Large Ion Collider Experiment



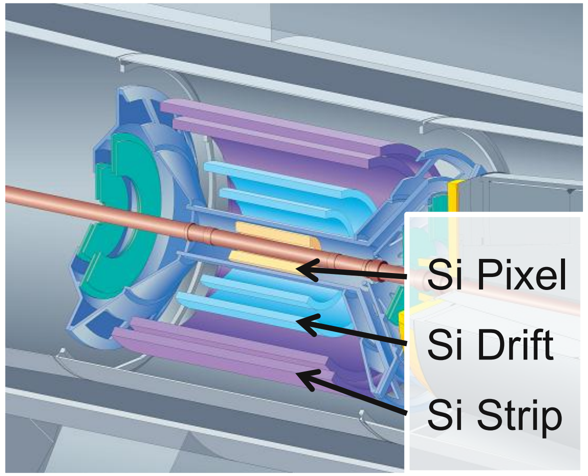
Radiation Hardness of Monolithic Active Pixel Sensors and Readout Electronics for the ALICE Inner Tracking System Upgrade

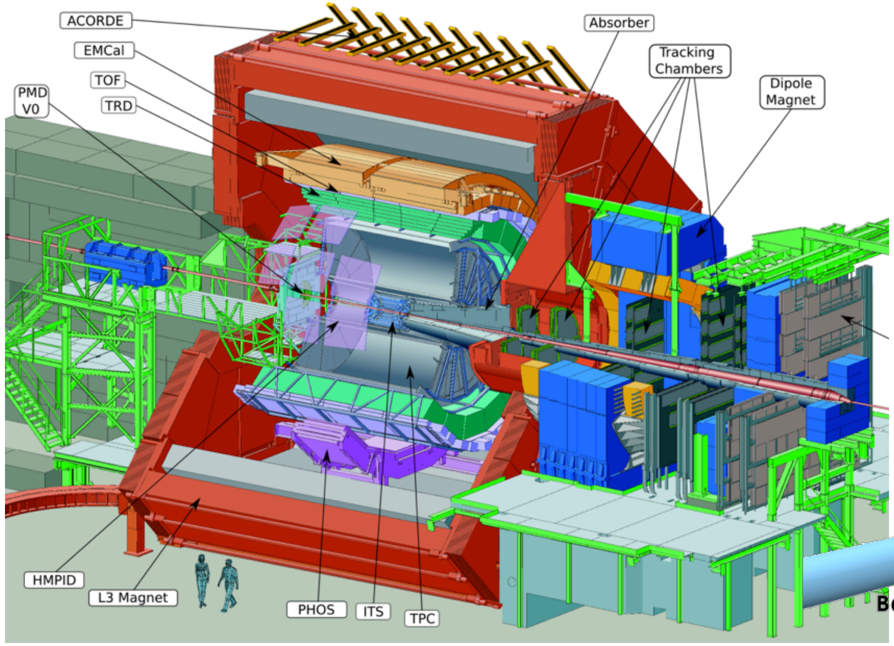
H. Hillemanns, CERN

OUTLINE

THE ALICE ITS UPGRADE PROPOSAL

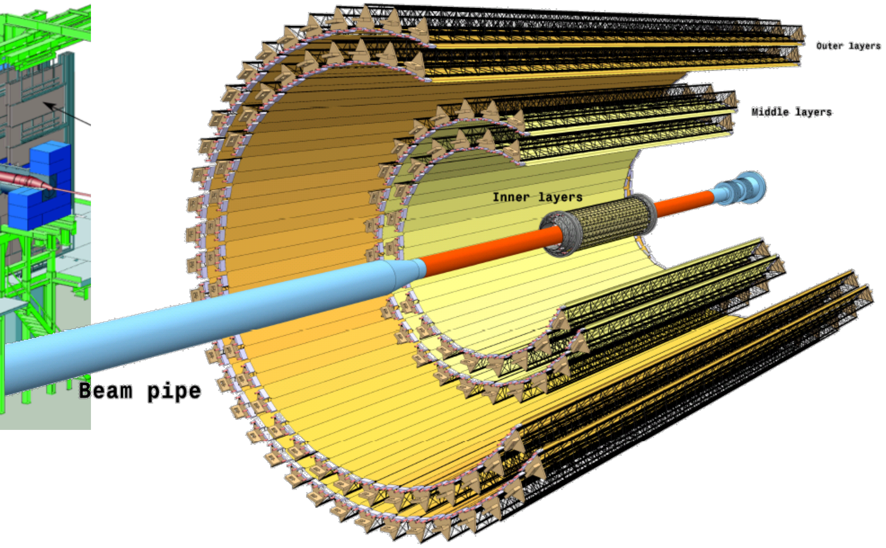
Goal: precision studies of QGP in heavy ion collisions





Objectives:

- Read out of all Pb-Pb interactions at 50kHz and and pp collisions at 200 kHz with minimum bias trigger
- Improve vertex reconstruction and tracking capability over a wide range of p_T
- Fast removal and insertion



➔ Requires a very fast and low material budget silicon tracker detector with high granularity to be installed in 2020

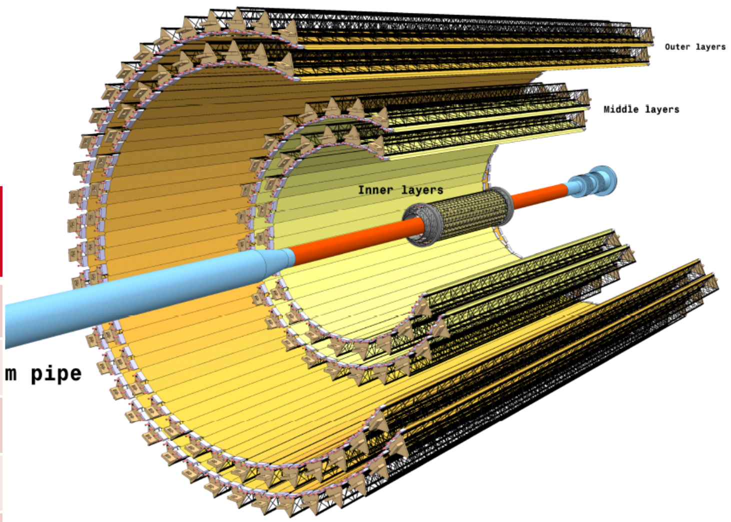
ITS UPGRADE DESIGN GOALS AND REQUIREMENTS

Design Objectives:

- Improvement of impact parameter resolution by a factor 3 in particular for very low p_T through reduction of :
  - Distance to IP (39mm -> 23mm)
  - Material budget(1.14% -> 0.3% X_0)
  - Pixel size
- Improvement of standalone tracking efficiency and p_T resolution

New ITS Layout

- 7 layers (3 inner, 4 outer layers)
- Radial coverage 23 – 406 mm
- 24120 Chips, 12.5 Giga Pixels
- 10.3m^2 Active Surface

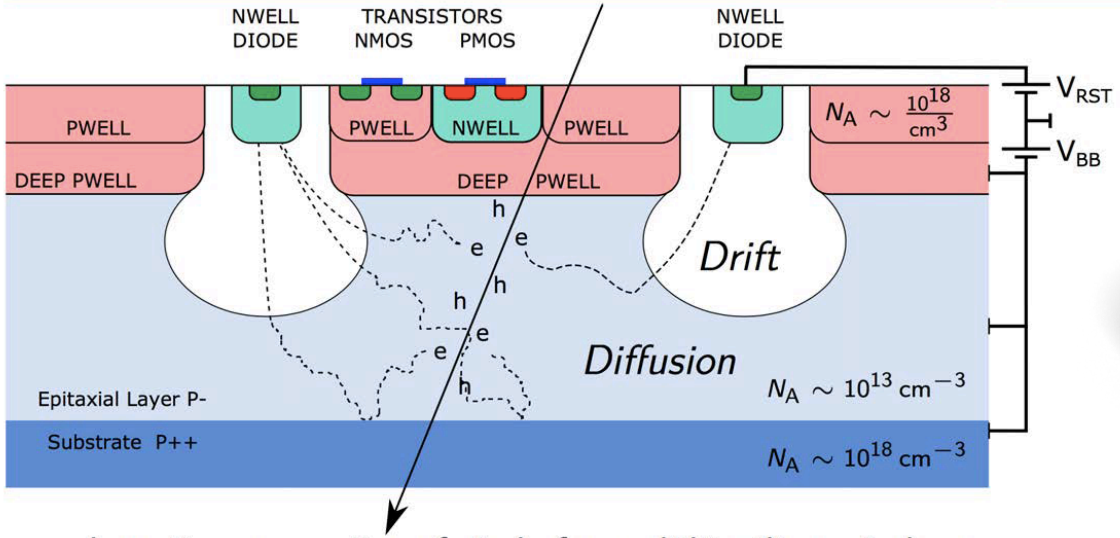


General requirements:

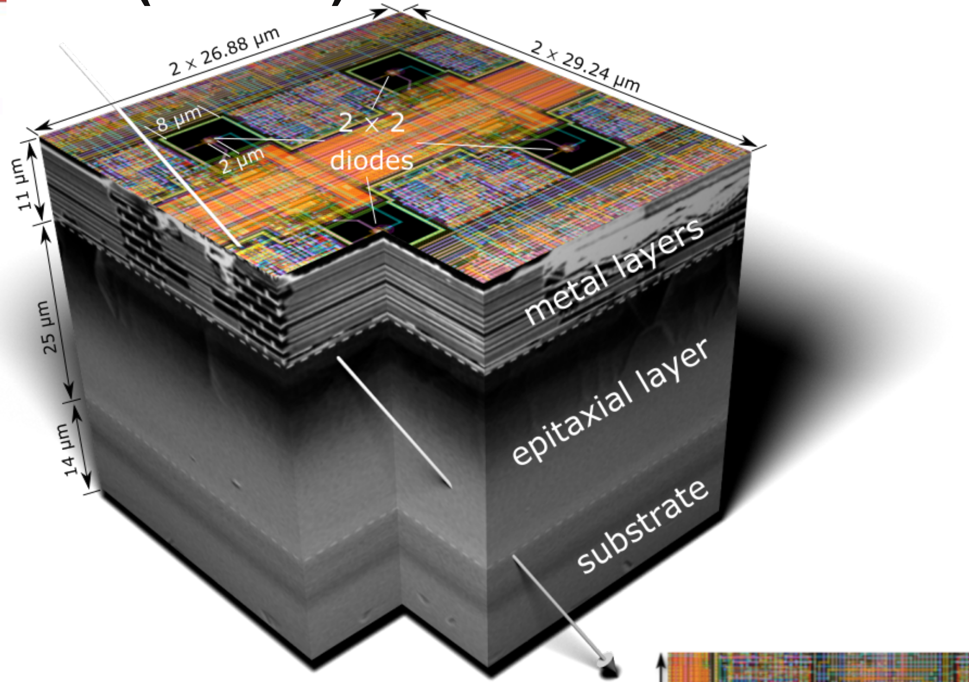
Parameter	Inner	Outer	Current Status (based on pAlpide3b/ALPIDE)
Max. Si thickness	50 µm	100µm	**ok**
Intr. Spatial Resolution	5 µm	~10 µm	**~5µm**
Chip Size	15mm x 30mm		**ok**
Max Power Density	<300 mW/cm^2	<100 mW/cm^2	**<35mW/cm^2**
Event Time Resolution	<30 µs		**~2µs**
Det. Efficiency	>99%		**ok**
Fake Hit Rate	<10^{-5} /event/pixel		**<<< 10^{-6} /event/pixel**
TID radiation hardness*	2.7 Mrad	100 krad	**Tested up to 2Mrad**
NIEL radiation hardness* (1MeV n_{eq} /cm^2)	1.7x10^{13}	1x10^{12}	**ok**

* Incl. a safety factor of 10

CMOS MONOLITHIC ACTIVE PIXEL SENSORS (MAPS)

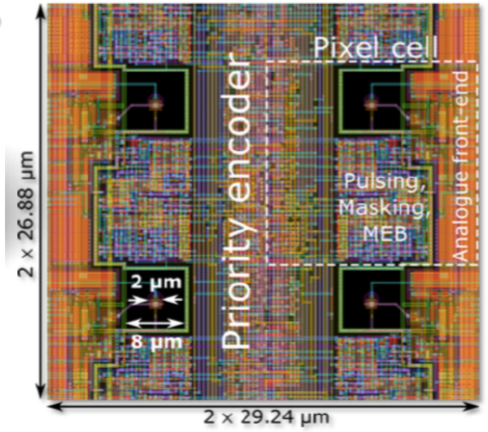


schematic cross section of pixel of monolithic silicon pixel sensor

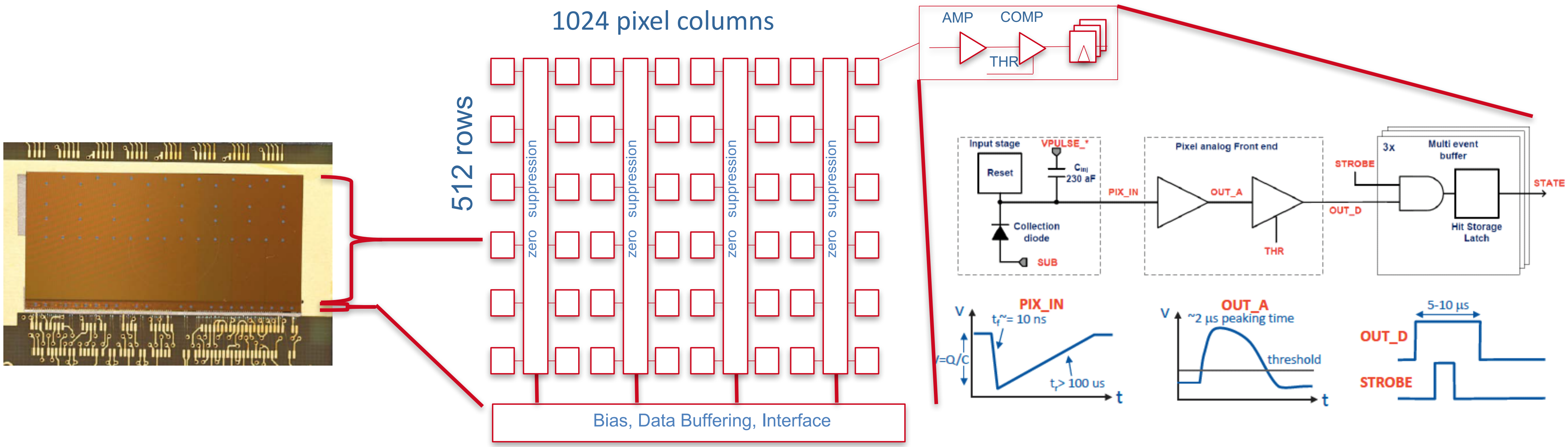


Key features MAPS manufactured in TowerJazz 180nm CMOS Technology:

- Reduced sensitivity to TID due to thin (3nm) gate oxides
- Quadruple well technology using deep p-well shielding: full CMOS circuits in the active sensor area
- High Resistivity epitaxial layer thickness of 25 µm (not fully depleted):
  - Increased depletion volume around the collection diode by applying reverse substrate bias VBB
  - Charge collection through drift (white) and diffusion (blue white) within 1ns and 100ns respectively
- Small n-well diode (2µm – 3µm, significantly smaller than pixel), thus lower input capacitance resulting in an increased input voltage



ALPIDE ARCHITECTURE



Key Concepts:

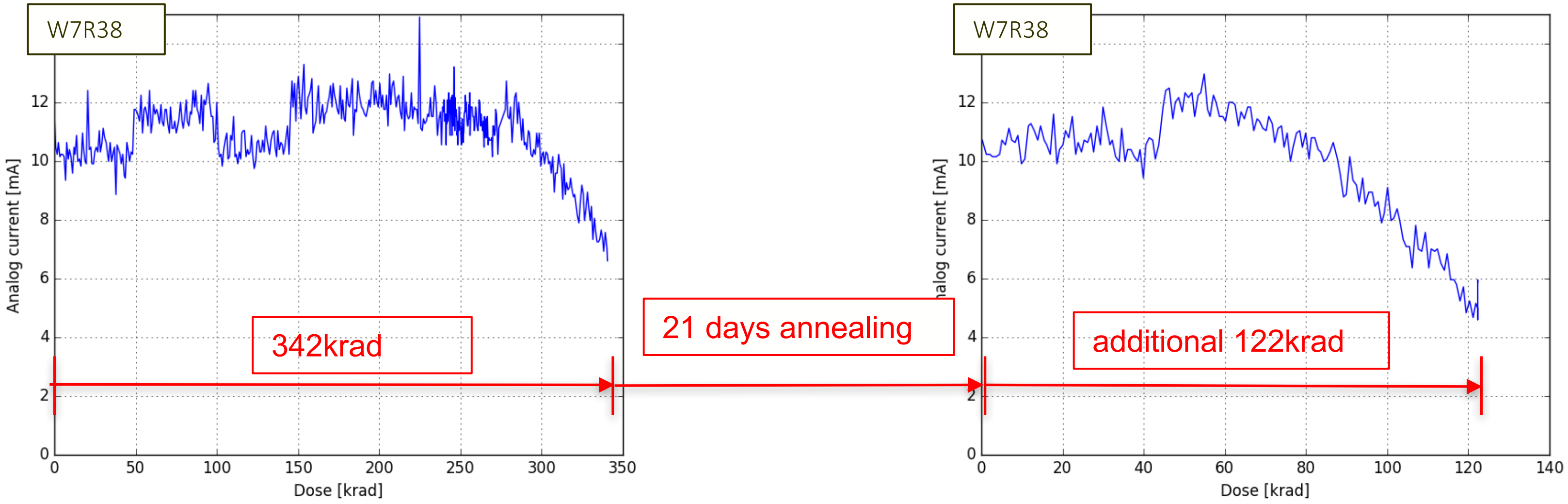
- In-pixel amplification
- In-pixel discrimination
- In-pixel multi hit buffer
- In-matrix sparsification through priority encoding

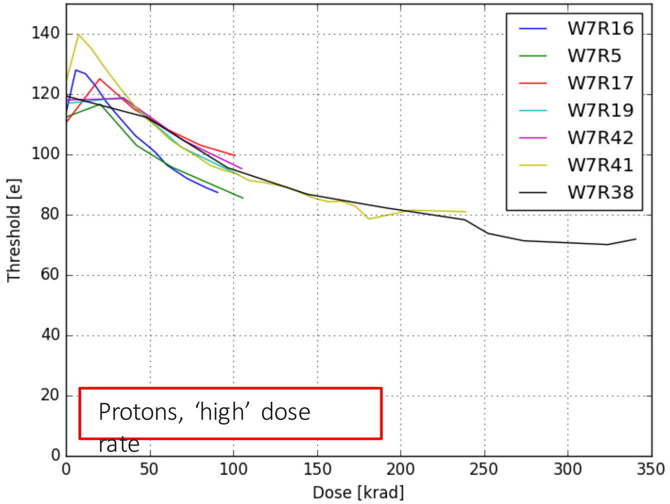
Key Features:

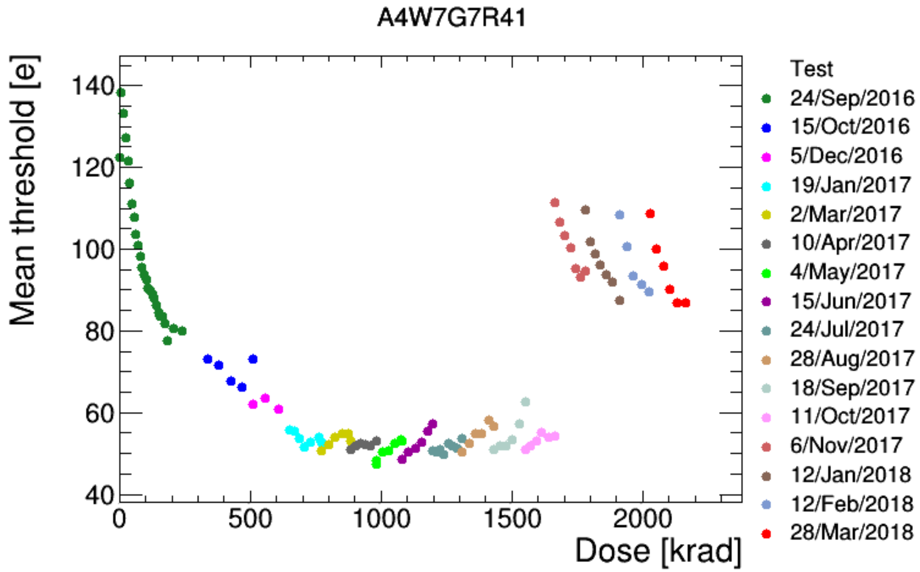
- Dimensions: 30mm x 15mm
- Pixel pitch: 29µm x 27µm
- Low power consumption: < 35 mW/cm2
- Global shutter: continuous (integration time <10µs) or triggered (200kHz) data acquisition

TID EFFECTS

- TID irradiation using a cyclotron (NPI Řež/Prague, 30 MeV/c protons)* and a Xray machine (CERN ATLAS team)
- Main observations during and after irradiation:
  - Some chip characteristics (thresholds, analogue supply currents, current DAC settings) affected as a function of TID, but also of dose rate (>> 0.1 krad/h (@50kHz Pb-Pb expected)
  - Changes in analogue supply current and current DAC settings anneal after a few days, effects thus presumably not visible for the maximum expected ALICE dose rate
  - Annealing of threshold values slow, but compensation though appropriate DAC settings

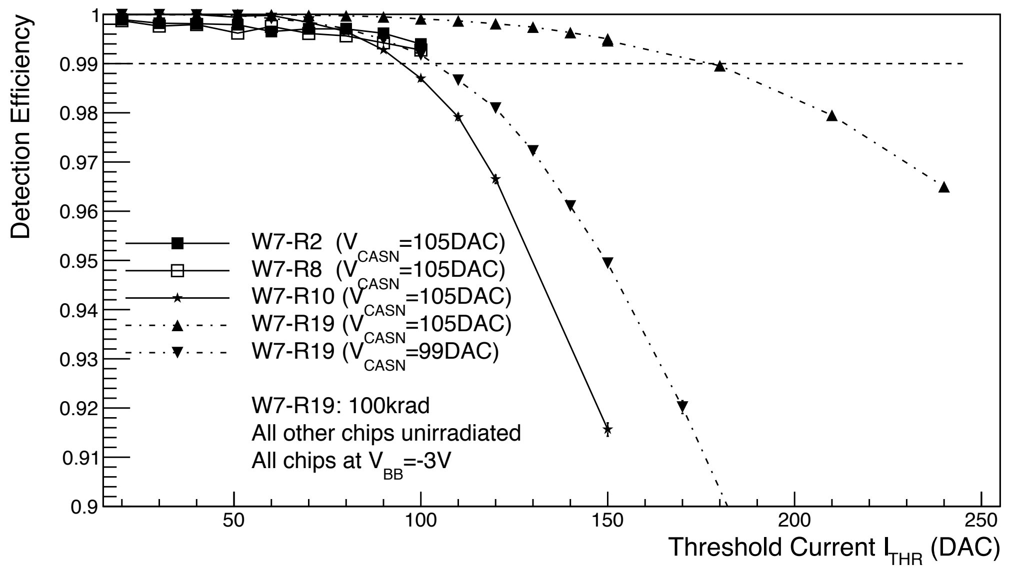


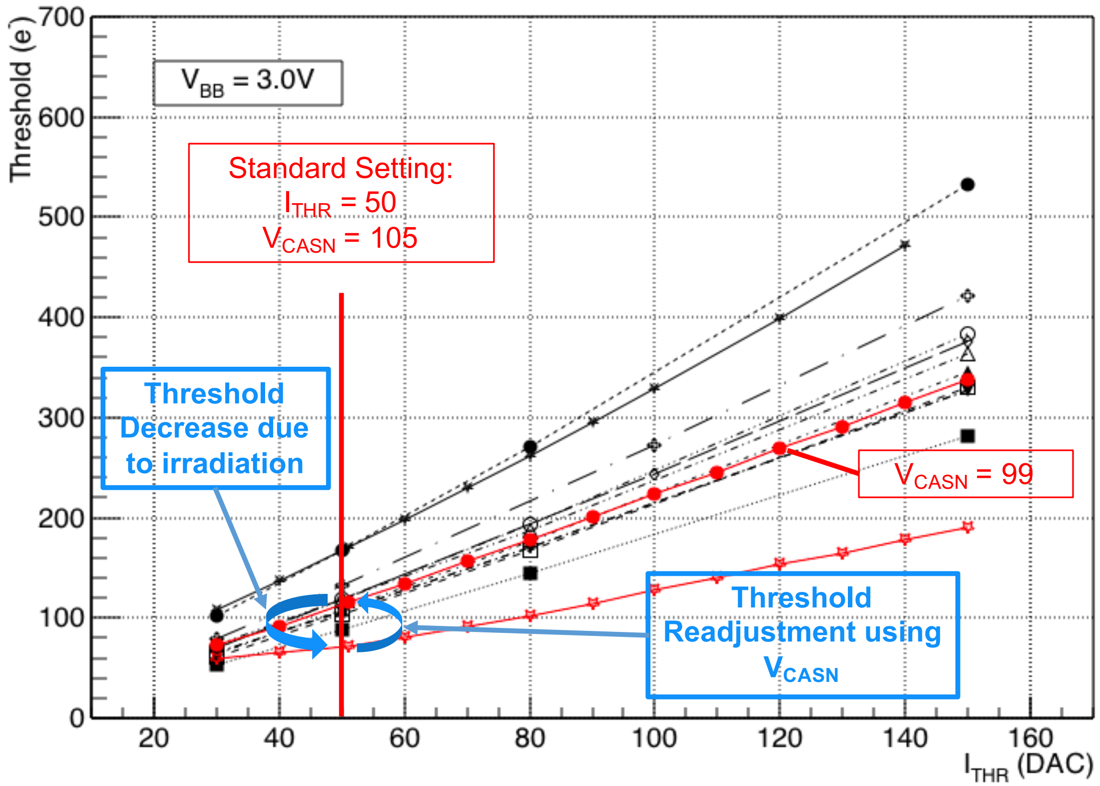




*CANAM infrastructure of the NPI CAS Rez supported through MŠMT project No. LM2011019

TID EFFECTS





Detector performance not affected after TID of 100krad (350krad see next slide)

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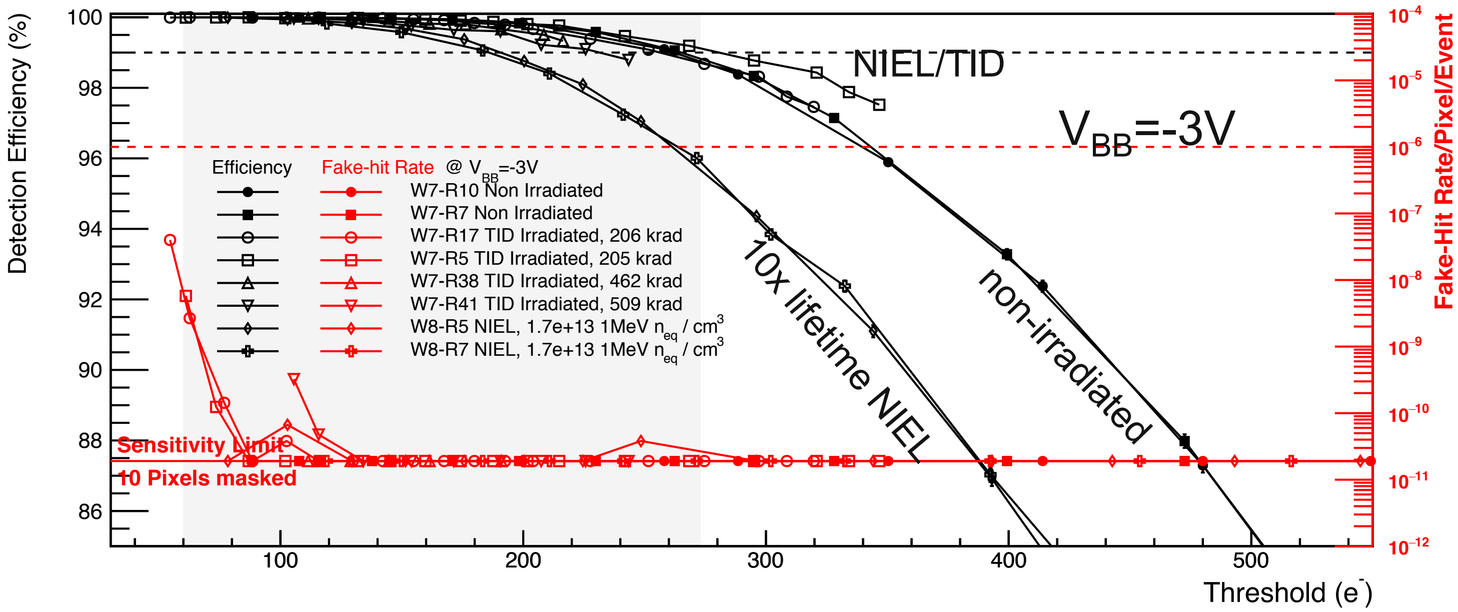
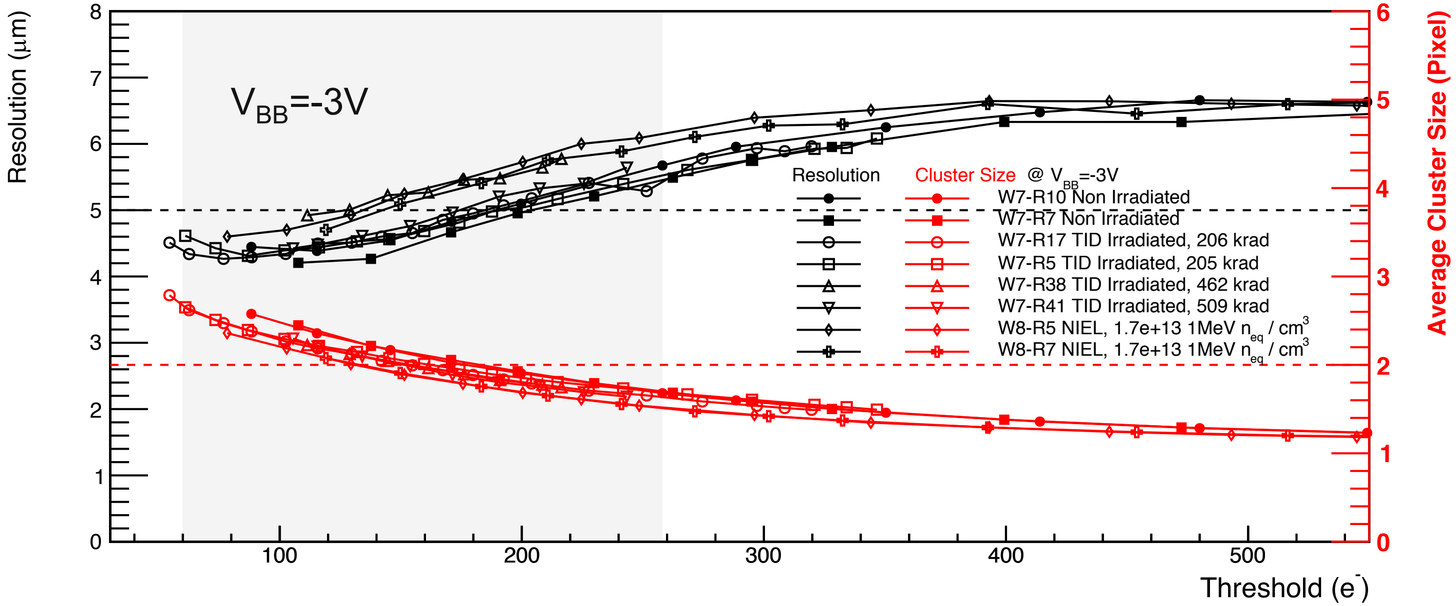
NIEL AND TID

- N-irradiation with a fluency of 1.7*10^{13} 1MeV n_{eq}/cm^2 at JSI (SL)*
- Sensor characterisation in various test beams
- Excellent detector performance before and after irradiation over a wide range of operational settings



Operational margin overlaid in grey



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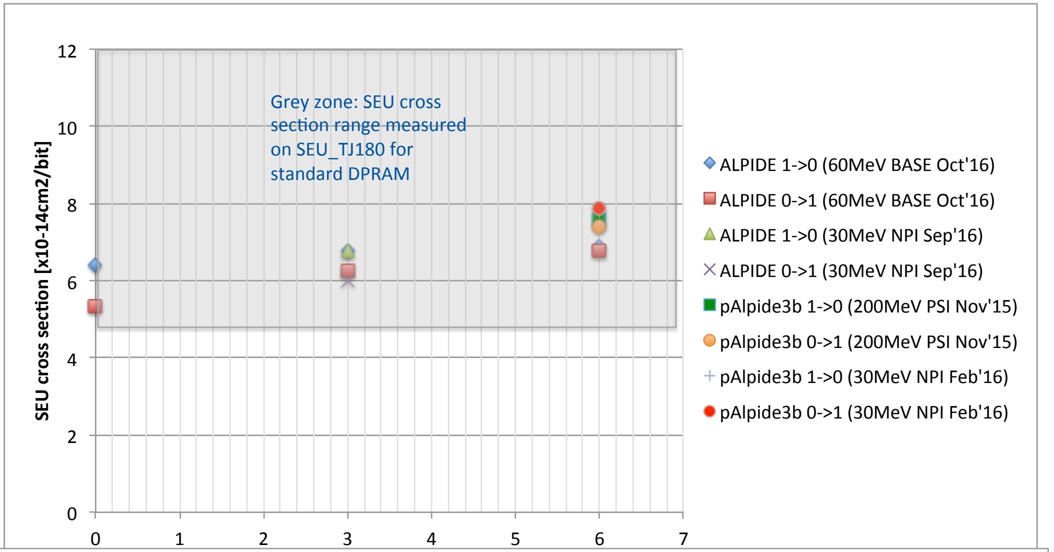
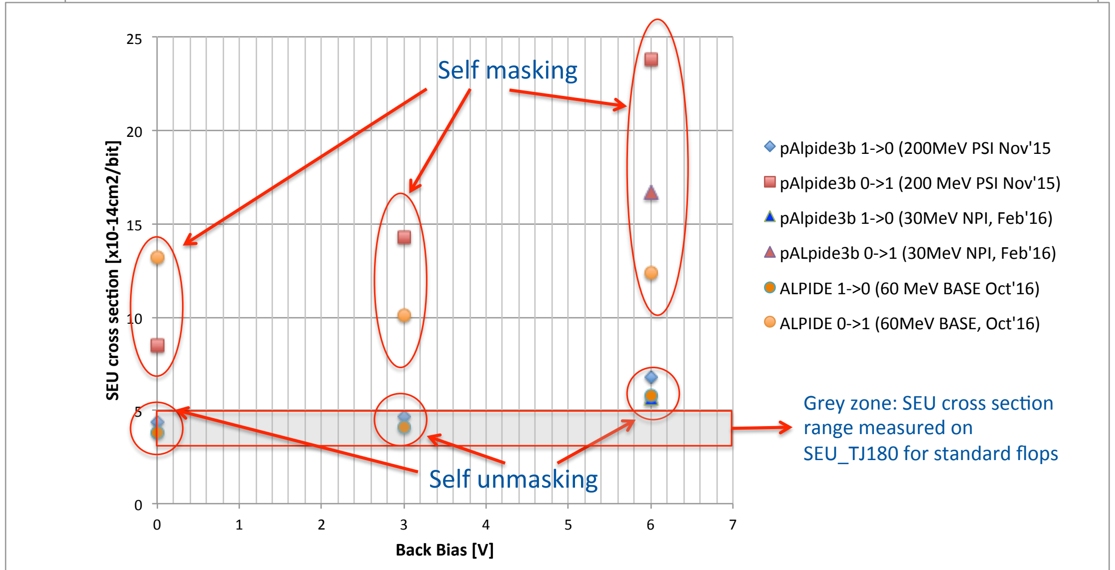
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 654168

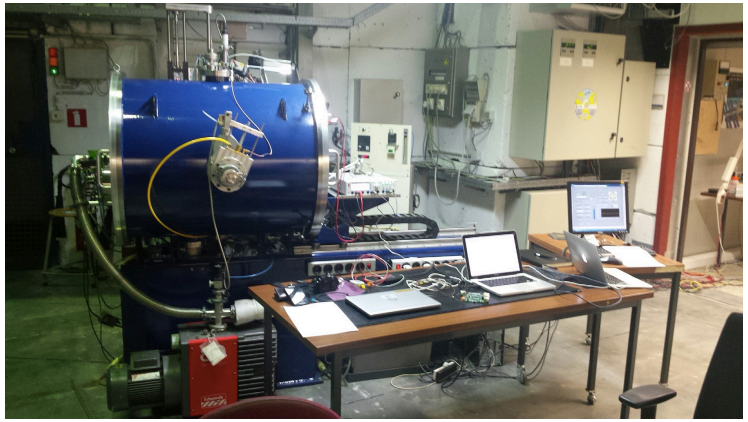
SINGLE EVENT UPSET

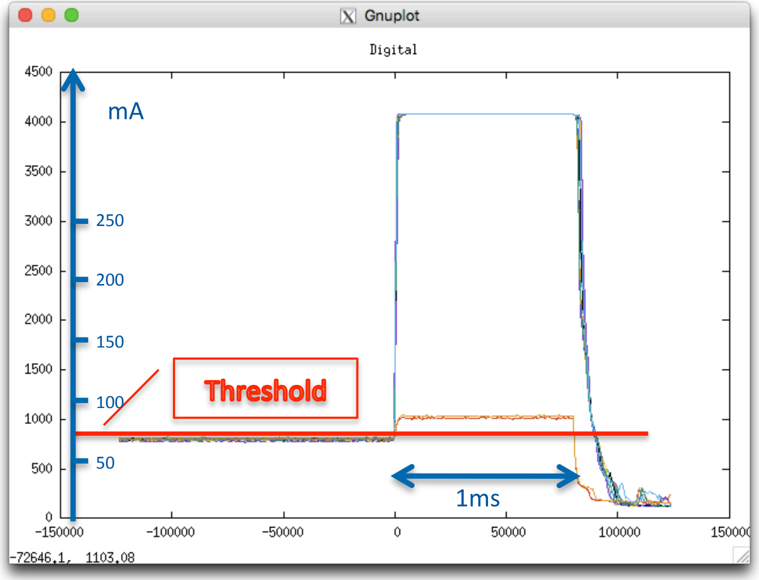
- pAlpide3b/ALPIDE SEU tests using proton beams at NPI, Prague (CZ) (30MeV/c) and at PSI (20 – 200 MeV/c)
- SEU cross section measurement of non SEU protected structures:
  - Region memories (FIFO)
  - Pixel mask bits
- Typical SEU cross section values:
  - Region Memory: 7e-14 cm^2
  - Pixel mask bit: 10e-14 cm^2





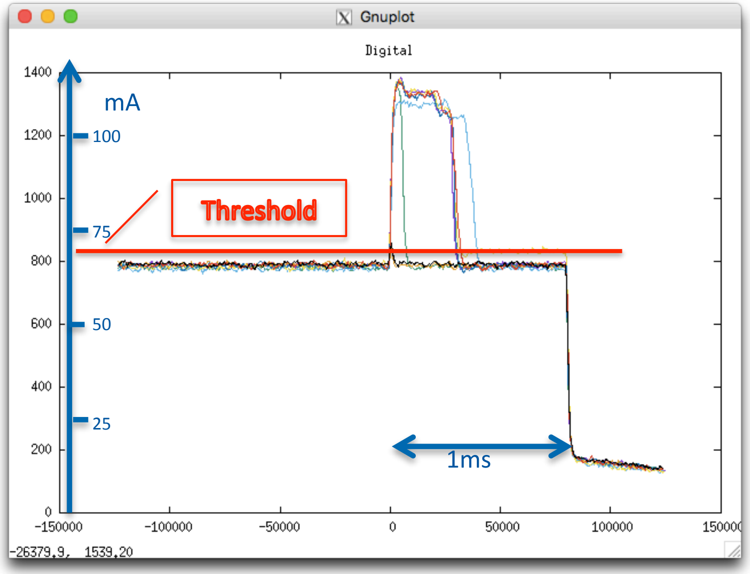
SINGLE EVENT LATCHUP TESTS (1/2)





SEL Tests at HIF (UC Louvain-la-Neuve) and BASE (LBL):

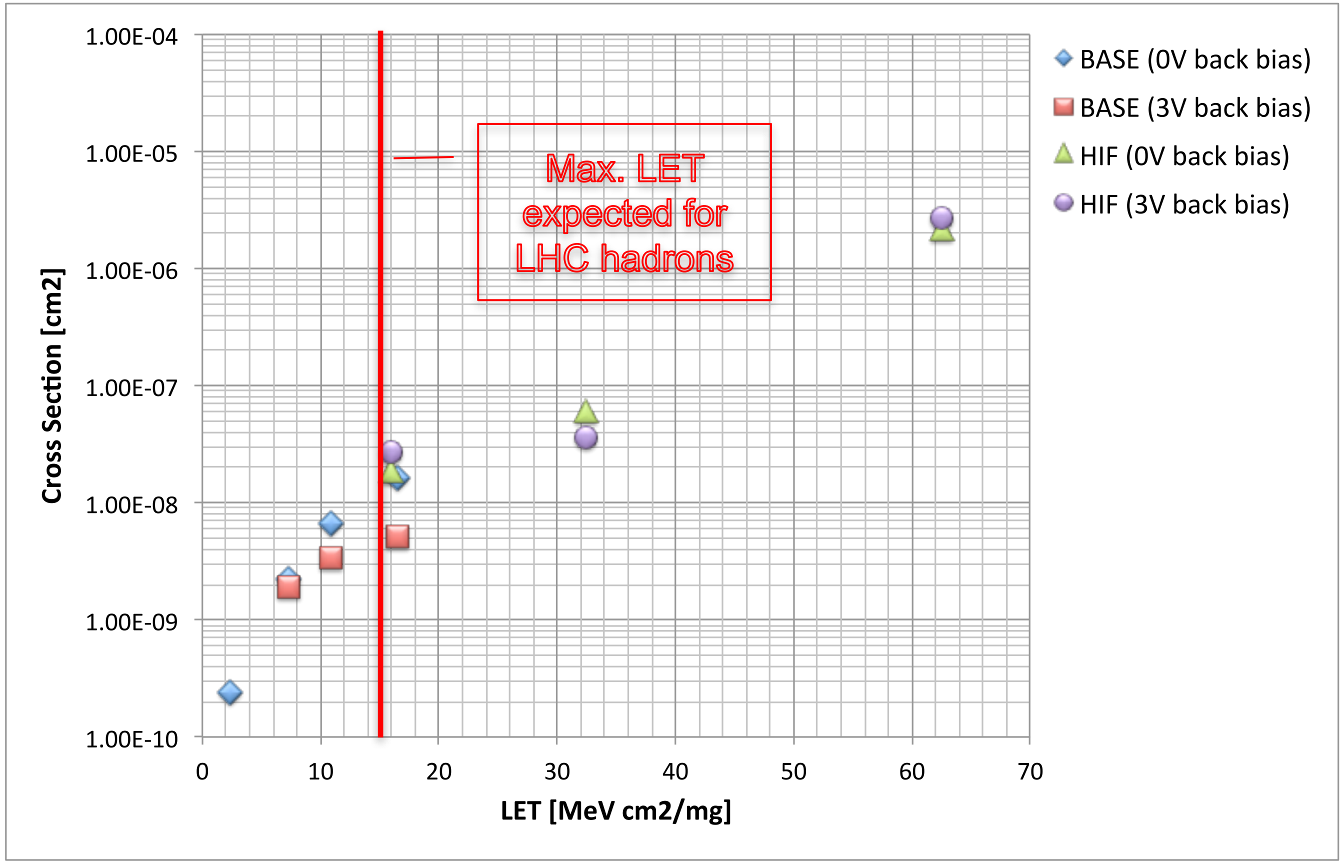
- Various ion cocktails covering a wide range of LET values (2.4 – 62.5 $MeVcm^2/mg$)
- Test setup with dedicated SW for overcurrent detection
- Thresholds (4mA) for analog and digital supply currents
- Chip power cycling after 1ms after overcurrent detection

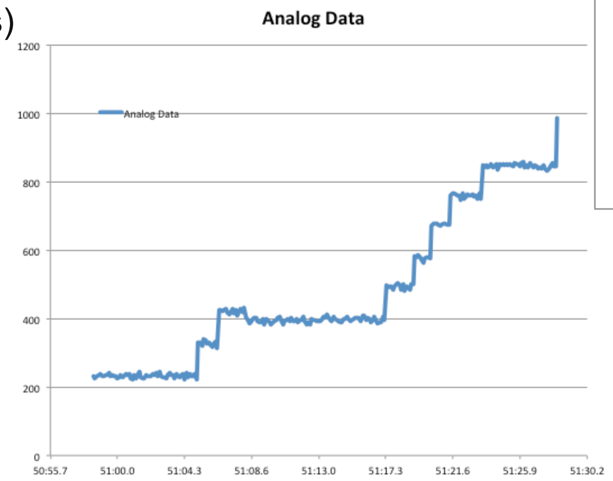


SINGLE EVENT LATCHUP TESTS (2/2)

Main Observations:

- Measurements at HIF and BASE in reasonable agreement
- No analog overcurrents observed
- Measured cross sections convoluted with expected ALICE particle spectrum results in about 1 LU per day for L0 (23mm, 108 sensors) at a maximum hit density of 1MHz (courtesy R.Garcia, CERN EN)
- All sensors survived latchup tests (even after cumulative latchups)

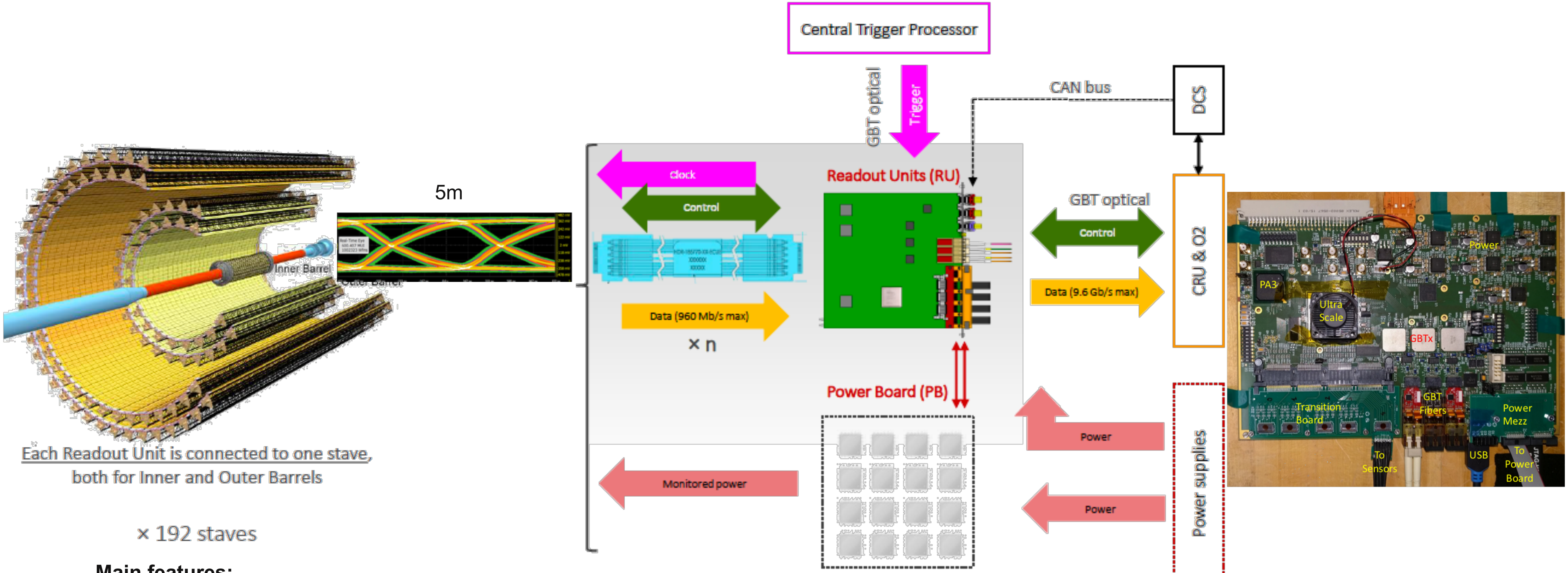




BASE results courtesy of L. Greiner, J.Szornel A.Collu, G.Contin (LBL Berkeley)

ALICE

READOUT ELECTRONICS RADIATION TOLERANCE VALIDATION (1/3)



Main features:

- One readout unit per stave (5m, 1.2/0.4 Gb/s data, 80Mb/s control, clock and power control), optically connected to common readout unit (CRU) and central trigger processor (CTP)
- CTP feeds trigger and checks CRU status
- CRU reads data and broadcasts control commands
- Data acquisition, packaging and detector control by O^2 system
- DCS access through O2 or CANBus

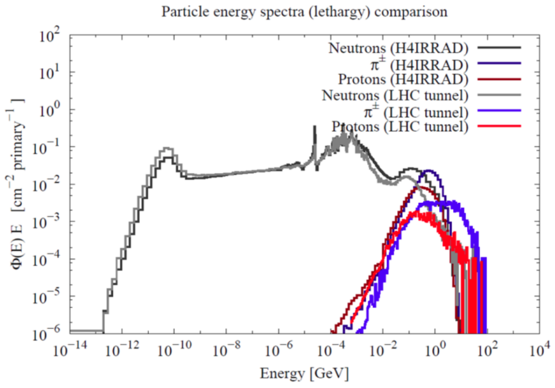
READOUT ELECTRONICS RADIATION TOLERANCE VALIDATION (2/3)

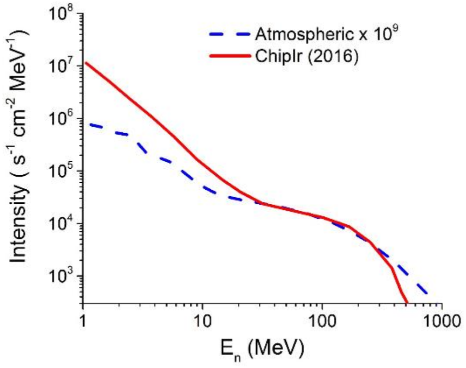
Radiation Environment

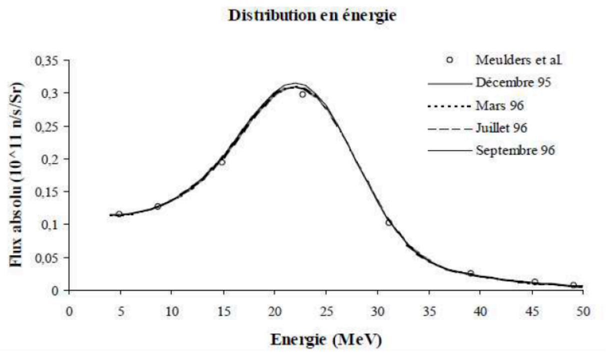
- Readout Electronics located in "Mini Frames" at about 1m from the beam axis and 3m from the IP
- Radiation levels (incl. safety factor 10):
  - TID: 10 krad
  - NIEL: 1.6 10^{11} 1MeV n/cm2
  - HEH Flux: 1 kHz/cm^2
- Requires SEE tolerant hardware and firmware

Extensive radiation test program both at component and system level:

- Firmware scrubbing verification using 30 MeV protons
- Full system test in the CHARM mixed radiation field
- DCDC (LMZ31710) verification using 23 MeV neutrons (UCL LIF)
- Full system tests using the ChipIr neutron facility (RAL)
- Power Board TID testing using the GIF++







READOUT ELECTRONICS RADIATION TOLERANCE VALIDATION (3/3)

Main Results:

- Everything works as expected
- Readout System fully TID tolerant
- SEL not an issue
- Scrubbing from auxiliary FPGA working and effective
- Data interruption in case of firmware upset has been measured and lasts on average one second for a the specific lane, few seconds if a reset of the FPGA is necessary
- Errors on clock resources or other key subsystem are negligible (too rare to gather any significant statistics).
- Commercial DCDC proved compliant with the task, one power glitch every 72 hours foreseen within the whole ITS.

Failure mode	Affected section	Estimated occurrence in ITS operations (average MTBF)			Corrective action	Downtime per occurrence
		IB	OB	Whole ITS		
Sensor data lane	1 sensor for IB ½ module for OB	22 - 40 h	4 - 6 h	3 - 5 h	Self-repairing	< 1 s >
GBT data*	1 full stave	29 h	10 h	7 h	30% self repairing, 70% reset by slow control	< 5 s >
Clock resources	1 full stave	Negligible	Negligible	Negligible	Reset by slow control	< 5 s >
Transceiver settings	1 sensor, IB only	> 932 h	–	–	Reset by slow control	< 5 s>
Flash memory	1 full stave	Negligible	Negligible	Negligible	FLASH reprogramming (30 s beam off, 30m beam on)	30 s – 30 m
[1]PA3	1 full stave	172 h	58 h	43 h	Reset by slow control	< 0 s>
[2]DCDC power glitch	1 full stave	294 h	98 h	71 h	Power cycle	< 10 s >

* Data for the non-TMR block, final version will use TMR protected block. This failure mode also include sensor control and clock failures.

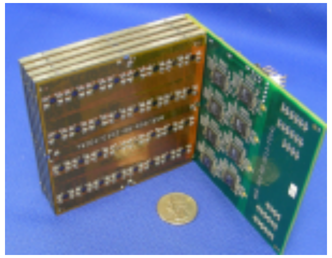
[1] When PA3 get stuck the main FPGA is not compromised, and therefore no downtime occurs. TMR of key block in PA3 firmware will further improve that.

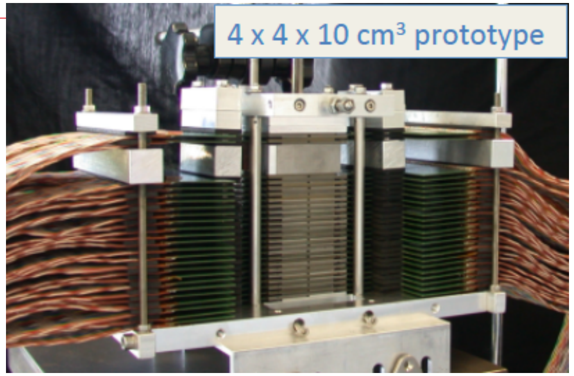
[2] Considering 200 RU with 8 DCDC each (20% overestimation)

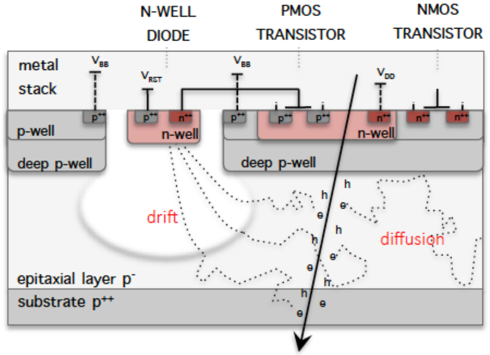
DEVELOPMENTS FOR THE FUTURE

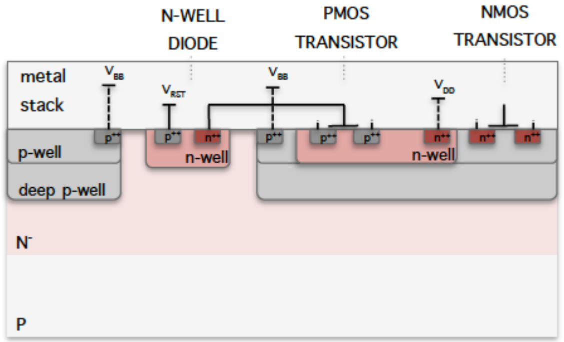
What's next ?

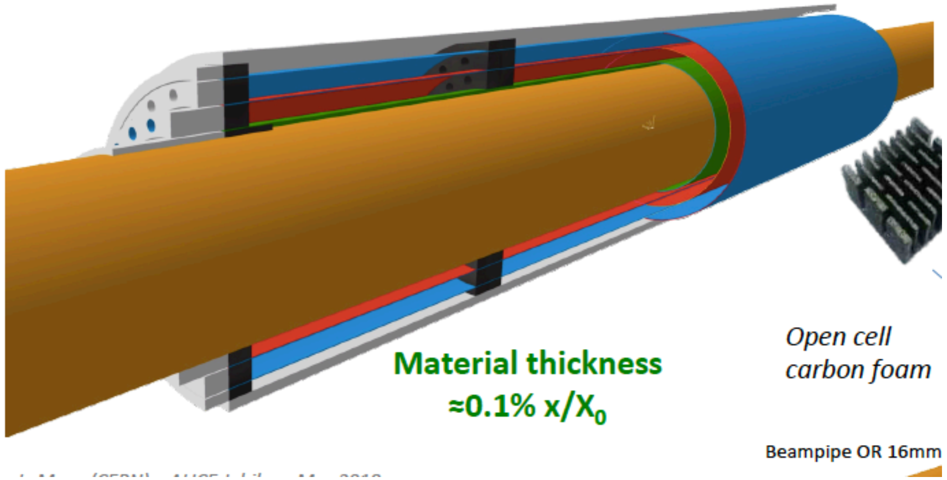
- The use of MAPS in various detector concepts for future experiments requires the improvement of radiation tolerance and reduction of material budget
- High granular digital calorimetry:
  - Multilayer Si-W pixel and pad readout
  - Extremely compact, small Molière radius
  - Very good linearity and energy resolution
- Modified CMOS process:
  - No circuit design change necessary
  - Full depletion through planar n⁻ -p junction
  - Use of ELT nmos transistors
- Ultrathin sensors:
  - Large sensors using stitching technology
  - Chip thickness <50µm
  - Cooling through air flow











SUMMARY AND OUTLOOK

- The upgrade of the ALICE ITS requires a new, fast, low material budget and radiation hard Si tracker
- Based on its features, the TowerJazz 180nm CMOS technology has been chosen as baseline technology for ITS
- Excellent detector performance in terms detection efficiency and fake hit rate after a TID of 350krad and a NIEL irradiation of 1.7×10^{13} 1 MeV n_{eq}/cm^2 s
- Measured cross sections for SEU and SEL are not considered to be a risk for the operational stability of the ITS
- TID effects will be monitored on a longer time scale for various irradiation scenarios
- Radiation tests on full modules with readout units working stable as expected
- Ongoing future development to address radiation hardness and ultrathin sensors as well as the use of MAPS in calorimeters