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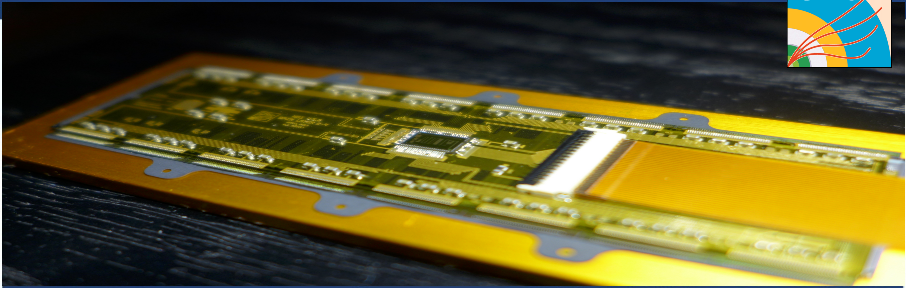

Phase I upgrade of the CMS pixel detector

24 November 2016 - PhD Seminar, Zürich

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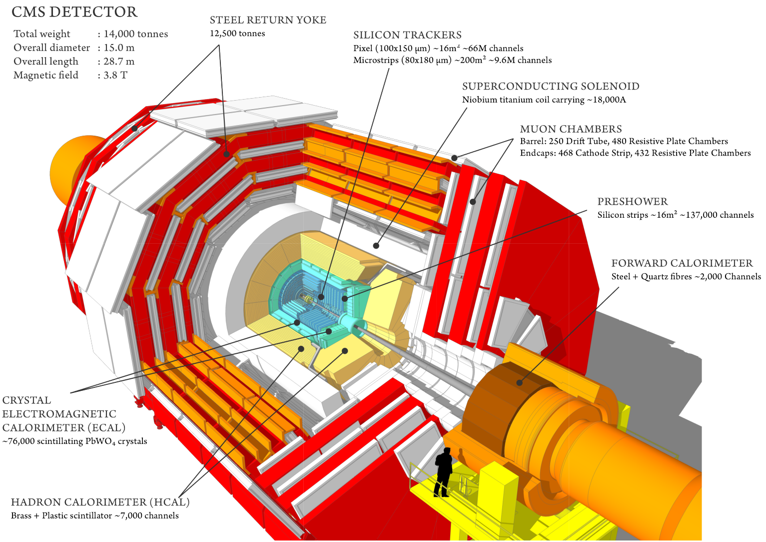
Outline

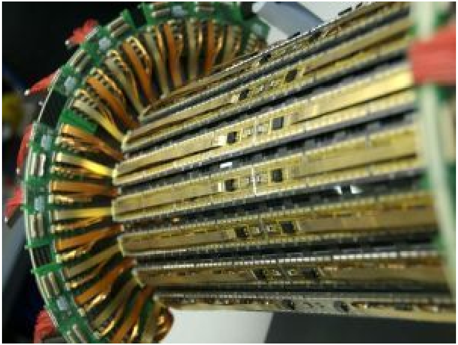
- The CMS detector at the LHC
- The pixel detector of CMS and its phase I upgrade
- Read-out chips (ROC) for the upgraded pixel detector
- Radiation hardness and high-rate efficiency of the ROCs
- Module assembly and testing procedure
- Current status of detector assembly

The CMS detector at the LHC



The pixel detector of CMS

- Measures the tracks of charged particles by interpolating the interaction points with several layers of detecting material
- Allows the reconstruction of primary and secondary vertices

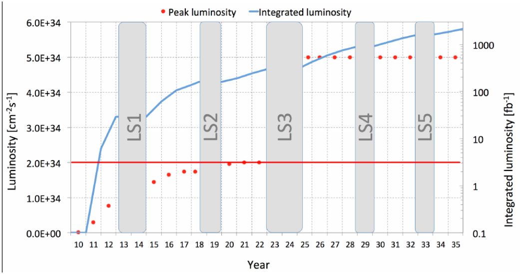


- Three layers in the barrel
- Two disks in each endcap
- 66 million read-out channels
- Resolution of 10 µm in $r\phi$ and 24 µm in z

- Operated from 2009 until now with an excellent performance

Motivation for the upgrade of the pixel detector

- Present detector designed for a maximum instantaneous luminosity of $1 \times 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$
- Instantaneous luminosity is expected to reach $2 \times 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$ by 2020

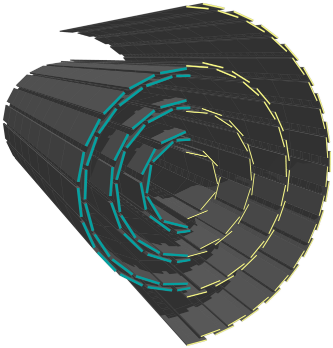


- Higher luminosity leads to inefficiencies as it exceeds the capability of the read-out chips
- Radiation damage leads to decreasing charge collection efficiency

Phase I upgrade of the pixel detector

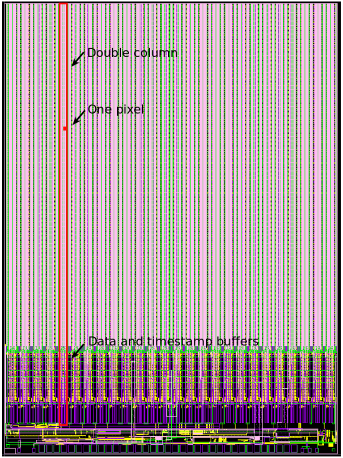
- To be installed in the 2016-2017 Year-End Technical Stop of the LHC
- Installation of a 4th layer in the barrel and a 3rd disk in each endcap
  $\Rightarrow$ Doubles the amount of read-out channels
- First layer closer to the beamline
- Decreasing material budget by moving the read-out electronics outside of the detector
- New Bi-phase $C0_2$ cooling
- On chip digitization of the data (40 MHz analog readout $\Rightarrow$ 160 Mbit/s digital readout)

$\Rightarrow$ Improved vertex resolution and tracking efficiency by up to 20%



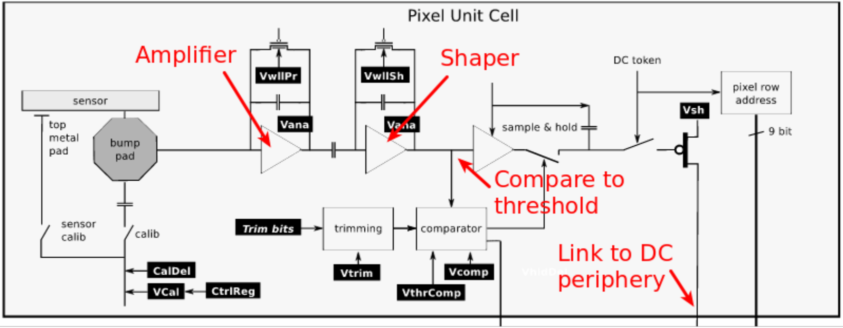
The ReadOut Chip (ROC) for the phase I upgrade of the pixel detector

- Based on the same technology (250nm CMOS) as the current chip
- Array of 4160 pixels arranged in double columns
- Data and timestamps are buffered in the double-column periphery
- ROC is tunable with different DACs (Digital to Analog Converters)
- There are two versions of the ROC:
  - ROCV2.1respin (L2-4)
  - PROC600V2 (L1) - faster read-out needed for higher particle fluxes closer to the interaction point

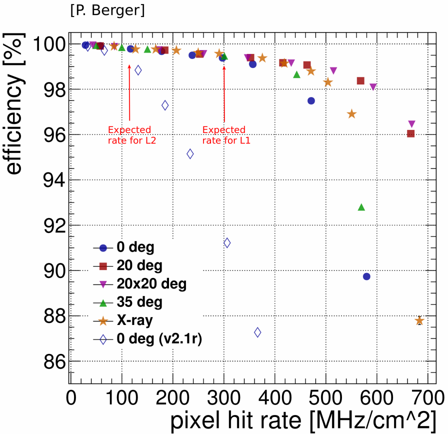


Signal processing of the ROC

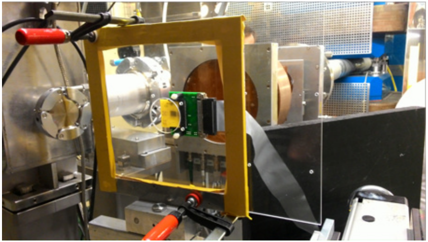
- Each pixel is bump bonded to a cell in the silicon sensor
- Charge is collected, amplified, shaped, and compared to a set threshold
- If it passes the threshold, the hit information is read out by the DC periphery and stored until L1 trigger validation



High rate efficiency of the ROCs



Beam test was performed at the Proton Irradiation Facility at PSI with a 200 MeV proton beam



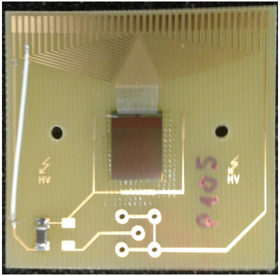
- Insert signals generated by the ROC in the read-out chain while exposing the chip to radiation
- The efficiency is the fraction of self-generated signals that are read out correctly and is the same for X-rays

Radiation hardness of the ROC

The upgraded pixel detector will be operated from 2017 to 2023

$\Rightarrow$ During this time an integrated luminosity of 300 fb^{-1} is expected

- How do the properties of PROC600V1 change after irradiation?
- How well does the chip perform after irradiation, can it be operated for its entire expected lifetime?
- Is the range of the tunable parameters sufficient for adjustment during operation?



Irradiation campaign

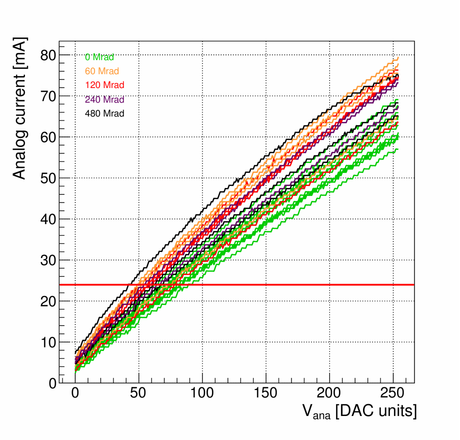
- 15 PROC600V1 without sensor were irradiated with a 23 MeV proton beam at Zyklotron AG in Karlsruhe (Germany)
- All ROCs are tested before and after irradiation

Irradiation dose [Mrad]	Fluence [Neq/cm^2]	Equivalence	# samples
0	0	/	15
66	$0.44 \cdot 10^{15}$	Layer 2	4
137	$0.91 \cdot 10^{15}$	Layer 1	5
265	$1.77 \cdot 10^{15}$	/	3
495	$3.3 \cdot 10^{15}$	/	3

NB: Most of the results shown here were obtained with PROC600V1. No major changes are expected for PROC600V2.

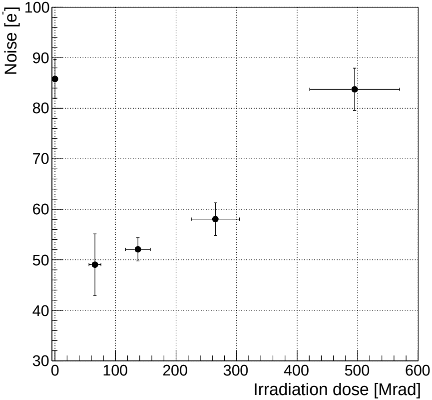
Few results from ROCV2.1respin are also presented

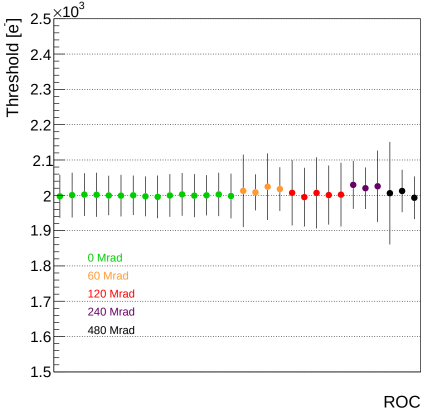
Analog and digital supply current



- Required supply currents for the digital and the analog part of the ROC can be supplied after irradiation after tuning the corresponding DACs

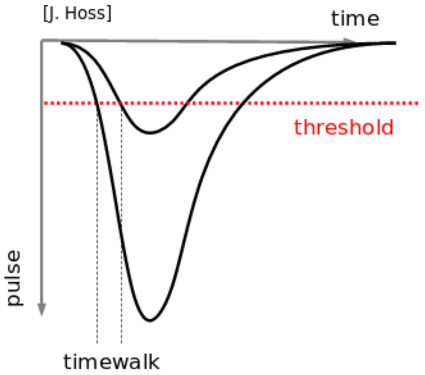
Noise and threshold

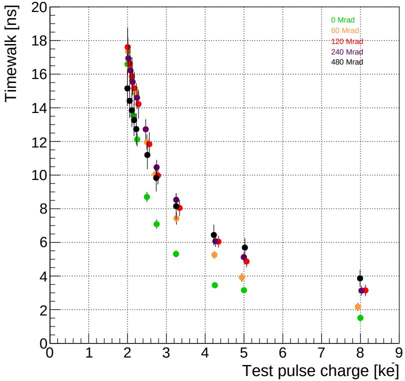




- Noise depends on the settings of the Feedback DACs
- Remains below 100 e^{-} also after the highest irradiation dose
- The threshold of PROC600 can be set to the same value before and after irradiation

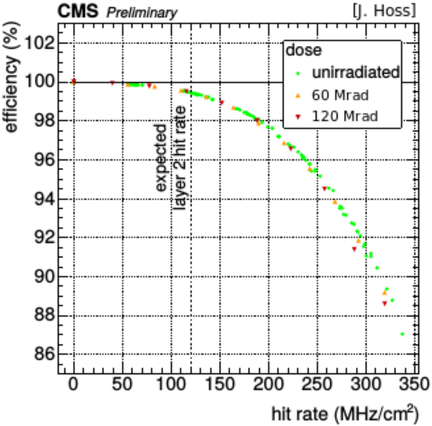
Timewalk



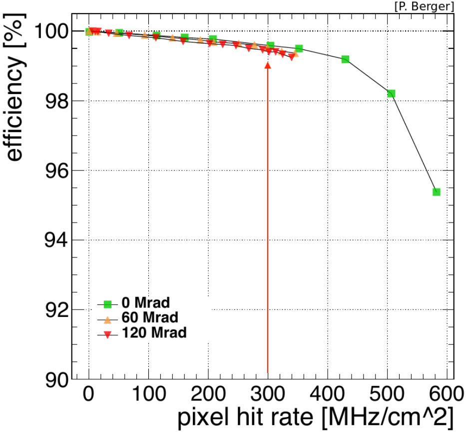


- Timewalk measured between a test pulse and high pulse
- Small increase of the timewalk after irradiation at higher test pulse charges
- Timewalk is well below the required 25 ns at all tested irradiation doses and test pulse charges

Efficiency



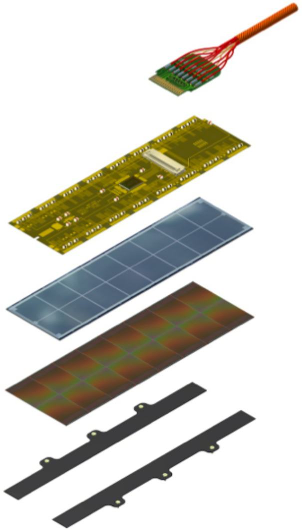
ROCV2.1respin (L2-4)



PROC600V1 (L1)

- Efficiency of the ROCs is 99.5% (ROCV2.1respin) and 99.4% (PROC600V1) for the corresponding expected rates (100 MHz cm^{-2} and 300 MHz cm^{-2}) at irradiation doses of up to 120 Mrad

Pixel detector modules

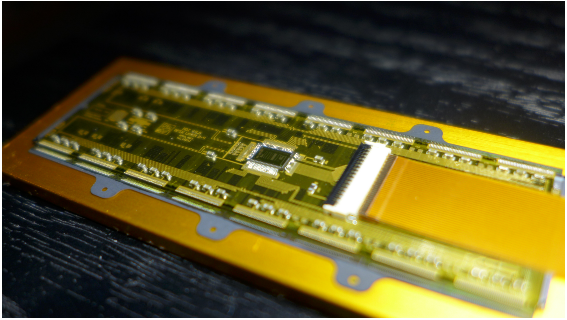


Module consists of:

- **Twisted pair cable** Provides power and signal to the module and is used for read-out
- **Token Bit Manager** Organises read-out of the module
- **High Density Connect** Distributes signal and power to the ROCs
- **16 ROCs** Collect the charge and process the signal
- **Sensor** Charge deposition by incoming particles
- **Basestrips** For fixation on the structure (only for L2-4)

Module qualification

- Every module is tested before installation to verify if it is working
- The DACs are tuned for every ROC to ensure a good functionality of the module



- Tested at -20° (temperature during operation) and +17° to ensure that the modules tolerate thermal stresses

Testing procedure for modules

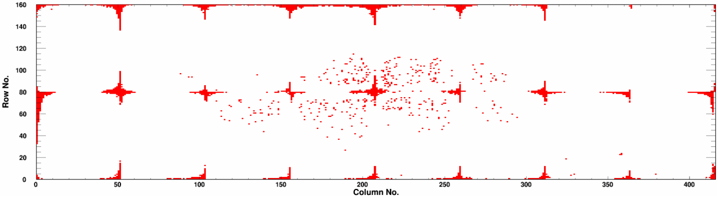
- Verify the programmability of all ROCs, set the supplied current and the timings for the TBM(s)
- Check the functionality of every pixel
- Measure the noise
- Set a uniform threshold amongst all pixels
- Optimize the pulse height
- Measure the leakage current

Using X-rays:

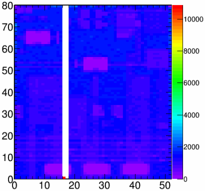
- Verify the bump bond quality
- Obtain conversion parameters between the pulse height (in ROC internal units) and electrons
- Measure the efficiency as a function of X-ray hit rate

Main reasons for rejected modules

- Too high leakage current indicating a defect in the sensor
- Defective data or timestamp buffers in a double column leading to reduced or zero efficiency
- Bad bump bond quality
- Other defects (defective HDIs, non programmability of a ROC or the full module, broken base strips, ...)



Module map of defective bump bonds



ROC X-ray hitmap

Module qualification for barrel pixel detector

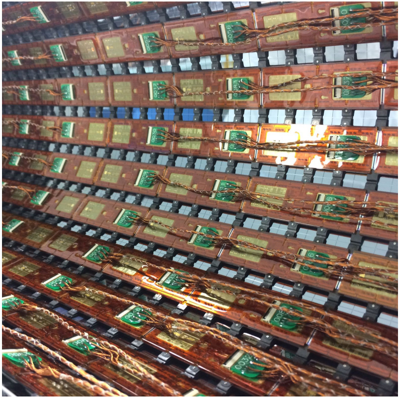
1184 modules are needed for installation
1845 modules have been produced by all centres
1317 modules passed the qualification

Collaboration between many institutes:

- L1: PSI & ETH (Switzerland)
- L2: PSI & ETH (Switzerland)
- L3: INFN (Italy), CERN (Switzerland), National Taiwan University (Taiwan), Helsinki Institute of Physics (Finland)
- L4: KIT, RWTH, DESY, Uni Hamburg (Germany)

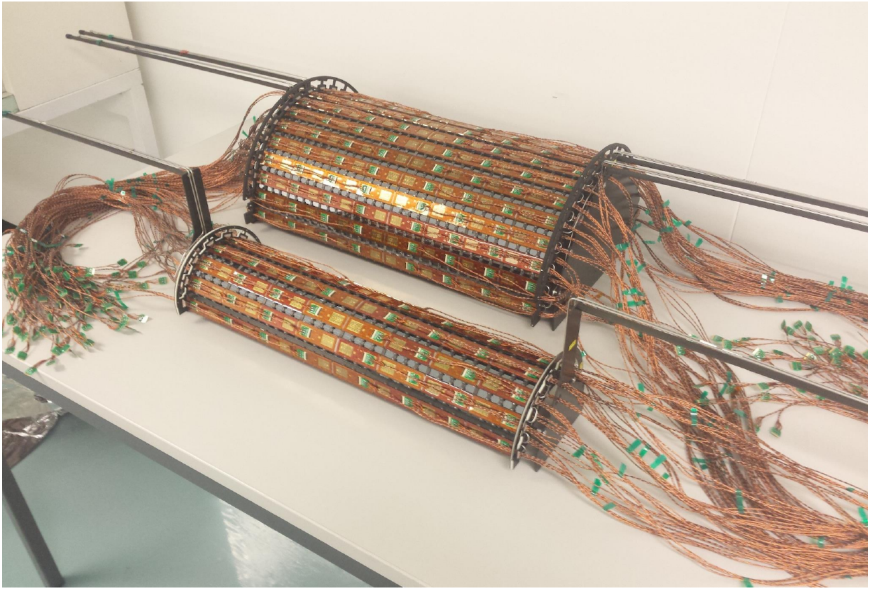
Current status

- Since last week, all modules needed for installation on all four layers have been assembled and qualified
- Module mounting on the structure and cabling of the modules is being completed this week at PSI
- Every module is quickly retested once mounted to replace modules damaged during mounting (<2%)
- Merging of the half shells is starting this week



- Merging of the detector and the supply tubes planned in December
- Transport to CERN and installation expected in February 2017

Layer 2 and 4 half shells



Conclusions

- Upgrade of the CMS pixel detector will be installed at the beginning of next year to maintain good efficiency with increasing luminosity
- The ROCs have been thoroughly tested in beam tests to measure their efficiency at high rates and in irradiation campaigns to test their longevity in high radiation environments
- All modules needed for installation in the detector have been produced, qualified and mounted on the structure