Development of hybrid silicon pixel detector and innovative electronic readout systems for experiments in the Large Hadron Collider of CERN (CMS)

Michele Salvatore

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Background

Bachelor's degree:

University of Perugia, Faculty of Engineering, Bachelor of Informatics and Electronics Engineering

Thesis: “Simulation of integrated radiation sensors in VLSI vertical technology(3D)” Tutor Dott. Daniele Passeri, co-Tutor Dott. Leonello Servoli (INFN Perugia)

Master's degree:

University of Perugia, Faculty of Engineering, Master of Electronics and Telecommunications Engineering

Thesis: “Performance analysis of vertically integrated CMOS radiation sensors for X-ray detection” Tutor Dott. Daniele Passeri, co-Tutor Dott. Leonello Servoli (INFN Perugia)

Outline

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- **CMS pixel upgrade phase I**
  - Present Pixel Detector
  - Upgrade Pixel Detector and Pixel Readout Chip
  - INFN Production
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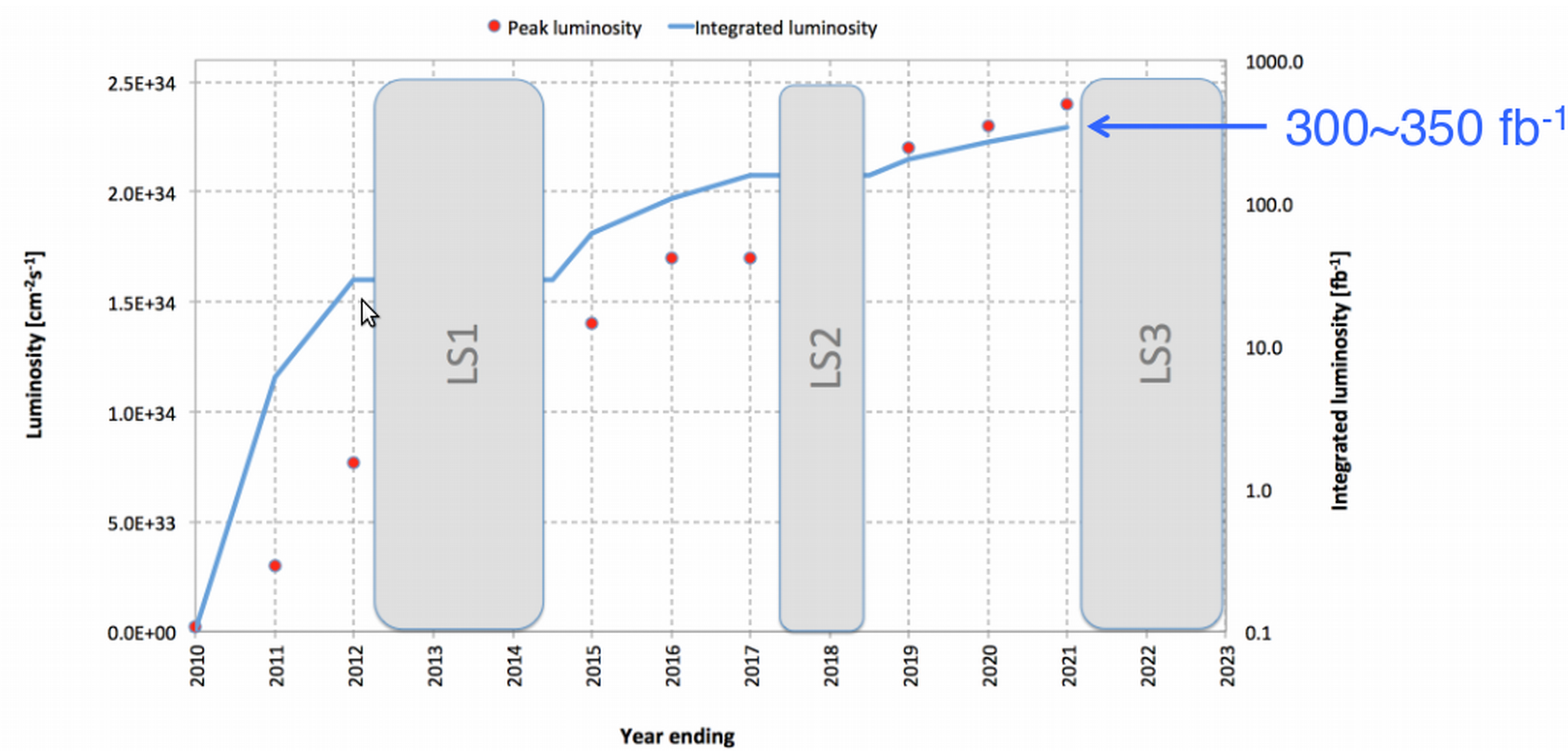
  - X-ray Calibration
- **CMS pixel upgrade phase II**
  - Pixel Challenges
  - Phase II Pixel
- **Conclusions**

Introduction

About CMS: CMS is a particle detector that is designed to see a wide range of particles and phenomena produced in high-energy collisions in the LHC.

Phase 1: Instantaneous luminosity L= 2×10^{34} $cm^{-2}s^{-1}$, Integrated luminosity ~ 100 fb^{-1}

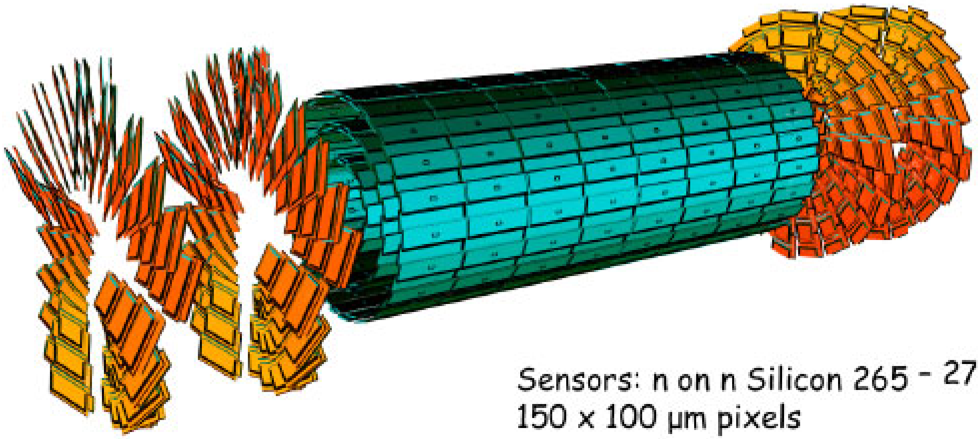
Phase 2: Instantaneous luminosity L> 2×10^{34} $cm^{-2}s^{-1}$, Integrated luminosity ~ 350 fb^{-1}



LHC Program

Present Pixel Detector

- L= 10^{34} $cm^{-2}s^{-1}$ @25 ns (25 pile-up events)

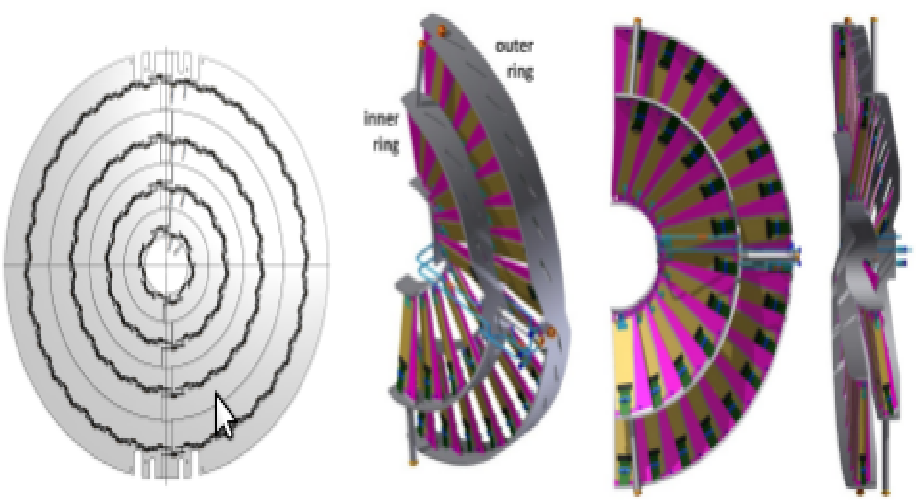


- **Barrel PIXels (BPIX)**
  - 3 layers (r=4.3, 7.2, 10.8 cm)
  - 48000 pixels, 0.78 m^2
- **Forward PIXels (FPIX)**
  - 2 disks (z = 34.5, 46.5 cm,6 cm < r < 15 cm)
  - 18000 pixels, 0.28 m^2

- Very good performance during RUN1:
  - Resolution 10 μm (R-Φ), 20-40 μm (Z)
  - Efficency> 99%
  - Crucial role in tracking and vertexing

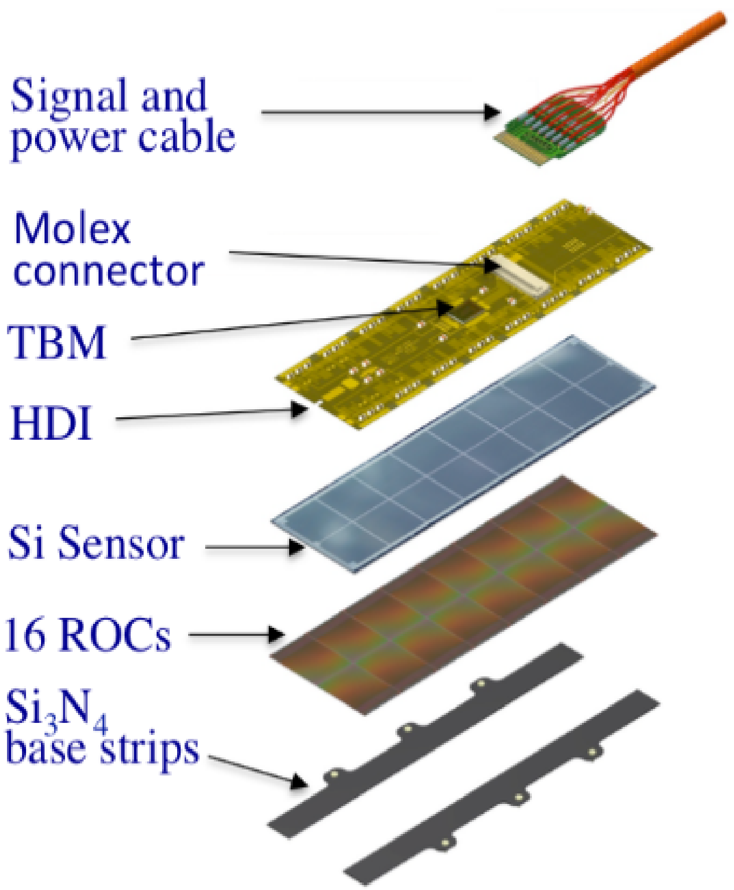
Upgrade Pixel Detector

- **Limitation of current pixel detector:**
  - Data loss at high occupancy and trigger rate
  - Degradation in performance due to radiation damage
  - Lower tracking efficiency at high pile-up
  - Degradation in performance due to material

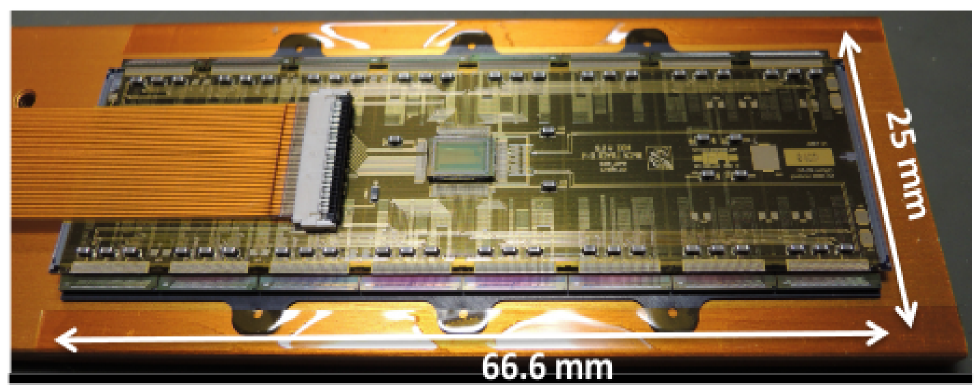


- **Upgrade detector:**
  - New Read-Out Chip (ROC)
  - 4 barrel layers (79M pixels)
  - 3 forward disks (45M pixels)
  - Reduce the material budget

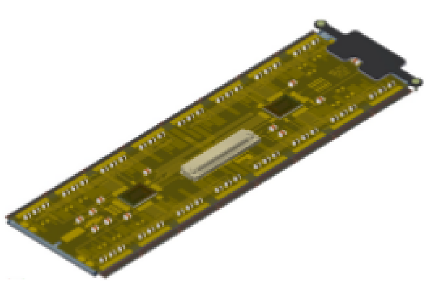
New Pixel Module



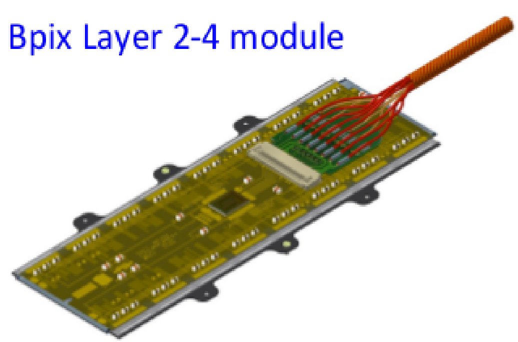
sensor type	n^+/n (pixel 100 x 150 μm^2)
sensor size	66.6 mm x 18.8 mm
sensor thickness	285 μm
ROC size	10.55 mm x 8.02 mm
ROC thickness	175 μm
granularity	16 x 52 x 80 (66560 pixels)
power	2.0 W
weight	< 3 g



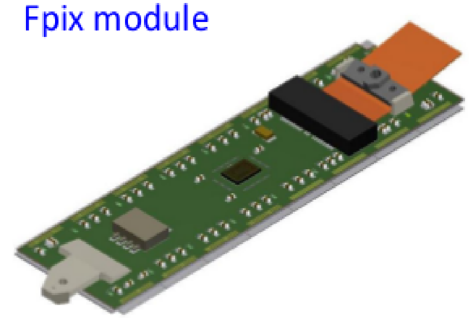
Bpix Layer 1 module



Bpix Layer 2-4 module



Fpix module



New Readout Chip (ROC)

PSI46DIG (250 nm, IBM): New digital ROC to solve data losses and inefficiencies:

- Based on present Analog Chip
- Digital instead of Analog Readout with following modifications:
  - ADC on CHIP
  - New fast digital readout links
  - PLL to provide higher frequencies
  - modification to control logic

ROC BPIX Layer 1:

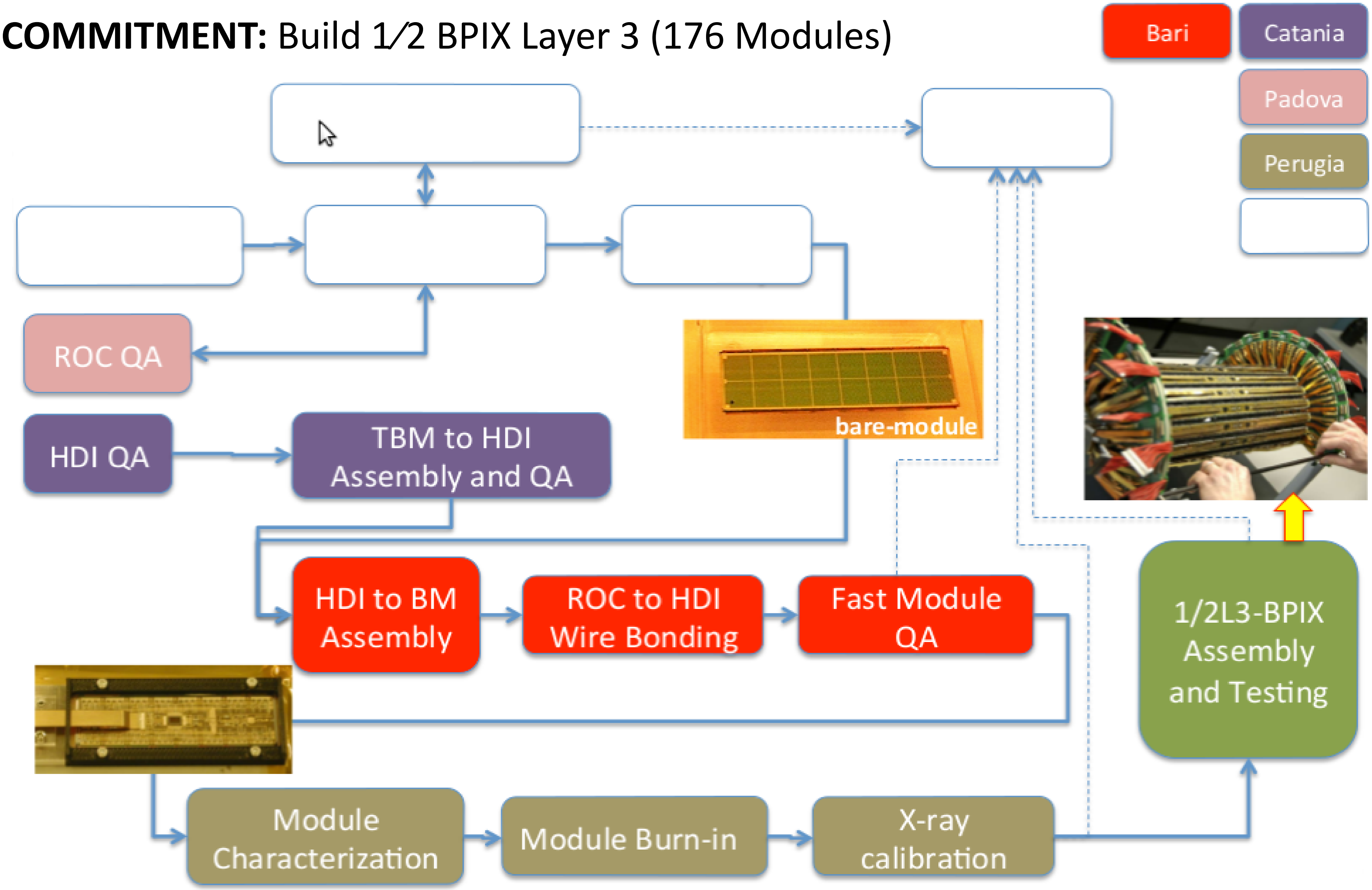
- Higher data rates and more elaborate buffer management
- Design done, submission started at the end 2014

ROC BPIX Layer 2-4 & FPIX:

- Three design iterations (2012-2014): final version psi46digv2.1respin
- Investigations in labs, beam test and irradiation

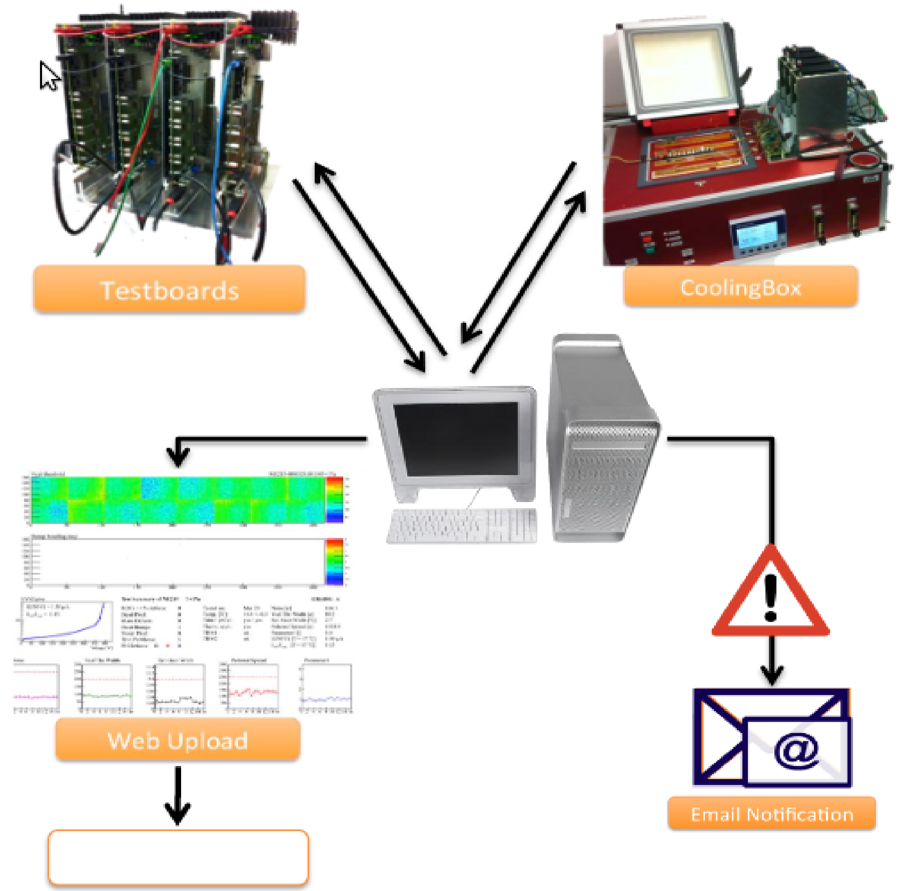
INFN Production

COMMITMENT: Build 1/2 BPIX Layer 3 (176 Modules)



Module Qualification

- **FullTest in the cooling box (elComandante):**
  - Cooling box: Complete test of the module response (using the pXar program) at -20° and +17° in temperature and RH controlled environment
  - Keithley electrometer: I/V curve of the module at -20°C and +17°C
  - Data analysis: using MoreWeb program

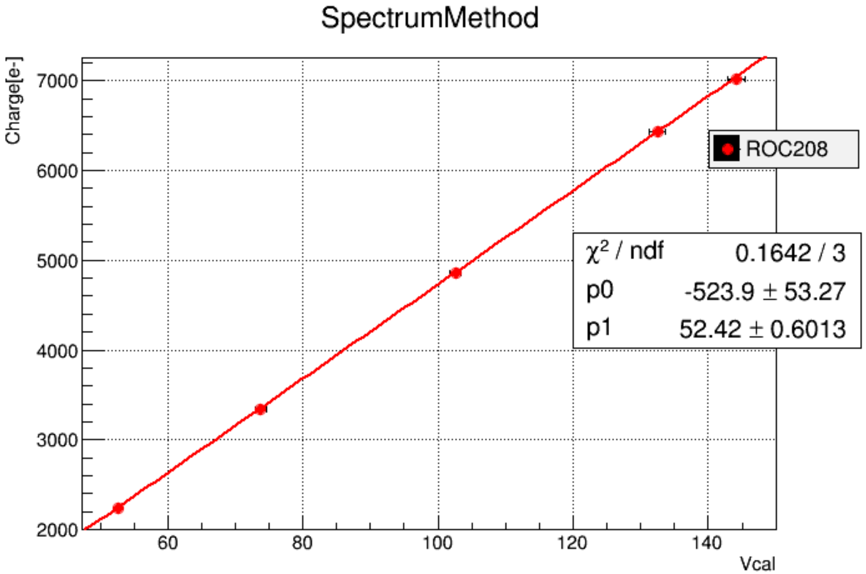


- **Activities:**
  - Software debugging: elComandate, pXar, MoreWeb
  - Jumo programming
  - Relative humidity monitoring
  - Peltier and module monitoring

X-ray Calibration

- **Fluorescence x-rays (well defined energy) is used to calibrate the pixel module:**
  - Emission of characteristic X-rays energy lines from materials that have been excited by high energy X-rays
  - Calibration of detector response expressed in electrons

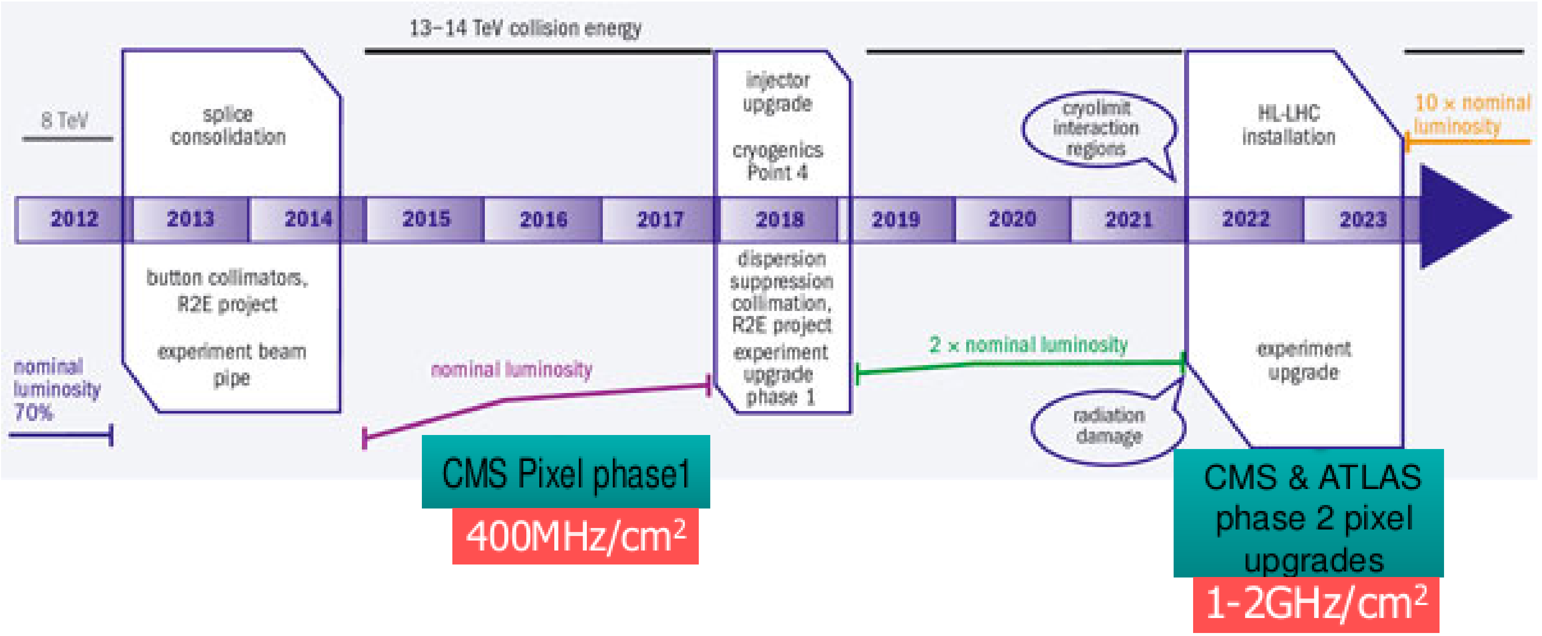
- **Activities:**
  - X-ray tube spectral characterization: Mini-X Amptek tube (40 kV - 90 µA) and Big X-ray tube (100kV – 4mA)
  - Design of setup devoted to the calibration of CMS modules
  - Software development (data analysis – automatic control)



Pixel phase II challanges

ATLAS and CMS phase 2 pixel upgrades very challenging:

- Very high particle rates: 500MHz/cm^2
- Hit rates: 1-2 GHz/cm^2 (factor 16 higher than current pixel detectors)
- Increased resolution (Smaller Pixel)
- Unprecedented hostile radiation: 10MGy(1Grad)



RD-53: R&D collaboration to address the challenges of making readout integrated circuits for the phase 2 pixel detector upgrades of ATLAS and CMS

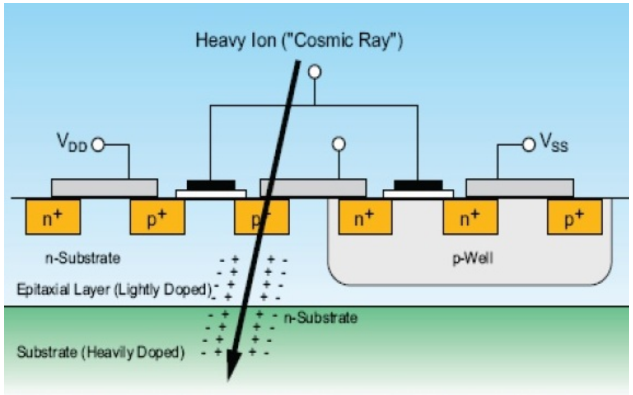
Pixel chip generations

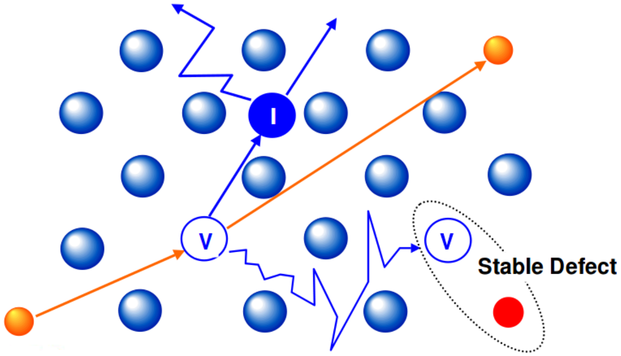
Generation	Current FEI3, PSI46	Phase 1 FEI4, PSI46DIG	Phase 2
Pixel size	100x150um^2 (CMS) 50x400um^2 (ATLAS)	100x150um^2 (CMS) 50x250um^2 (ATLAS)	25x100um^2 ?
Sensor	2D, ~300um	2D+3D (ATLAS) 2D (CMS)	2D, 3D, Diamond, MAPS ?
Chip size	7.5x10.5mm^2 (ATLAS) 8x10mm^2 (CMS)	20x20mm^2 (ATLAS) 8x10mm^2 (CMS)	**> 20 x 20mm^2**
Transistors	1.3M (CMS) 3.5M (ATLAS)	87M (ATLAS)	**~1G**
Hit rate	**100MHz/cm^2**	**400MHz/cm^2**	**1-2 GHz/cm^2**
Hit memory per chip	0.1Mb	1Mb	~16Mb
Trigger rate	100kHz	100KHz	200kHz - **1MHz**
Trigger latency	2.5us (ATLAS) 3.2us (CMS)	2.5us (ATLAS) 3.2us (CMS)	6 - **20us**
Readout rate	40Mb/s	320Mb/s	**1-3Gb/s**
Radiation	1MGy (100Mrad)	3.5MGy (350Mrad)	**10MGy (1Grad)**
Technology	250nm	130nm (ATLAS) 250 nm (CMS)	**65nm**
Architecture	Digital (ATLAS) Analog (CMS)	Digital (ATLAS) Analog (CMS)	Digital
Buffer location	EOC	Pixel (ATLAS) EOC (CMS)	Pixel
Power	~1/4 W/cm^2	~1/4 W/cm^2	**~1/4 W/cm^2**

Pixel phase II

- **Technology: a 65nm CMOS technology node has been identified as a promising technology for the implementation of HL-LHC pixel chips:**
  - Mature technology: available since ~ 2007
  - Long term availability (used extensively for industrial/automotive)
  - Access (CERN frame-contract with TSMC and IMEC)
  - Excellent radiation tolerance up to ~1MGy (To be confirmed for 1Grad)

- **Activities: for the phase II pixel is crucial to develop an adequate test system for radiation test. In particular we are going to measure:**
  - Radiation Damage from TID (Total Ionizing Dose): Gamma ray (^{60}CO)
  - Displacamente Damage: proton beams (LNL e LNS facilities)
  - Single Event Effects (SEEs): proton beam (LNL-LNS), ions (LNL-LNS), laser





Conclusions

Regarding the pixel upgrade phase I our work will be focused on the following tasks:

- Software development to readout each single pixel and to control the DAQ
- Software development to execute thermal cycle and to monitor temperature and humidity
- X-ray calibration based on monochromatic x-ray fluorescence

Whereas the activity on the radiation damage test for the phase II pixel will involve us with:

- Adequate test equipment construction for each subsytem (ADC, DAC, charge preamplifier, memory, ...)
- Test in different facilities will be done to verify Displacament Damage and Single Event Effects (Laboratori nazionali di Legnaro (LNL) e Catania (LNS)