Karlsruhe Institute of Technology

Module production and testing for the CMS pixel Phase 1 upgrade

GK Plenary Workshop, 28th – 30th September 2015, Freudenstadt

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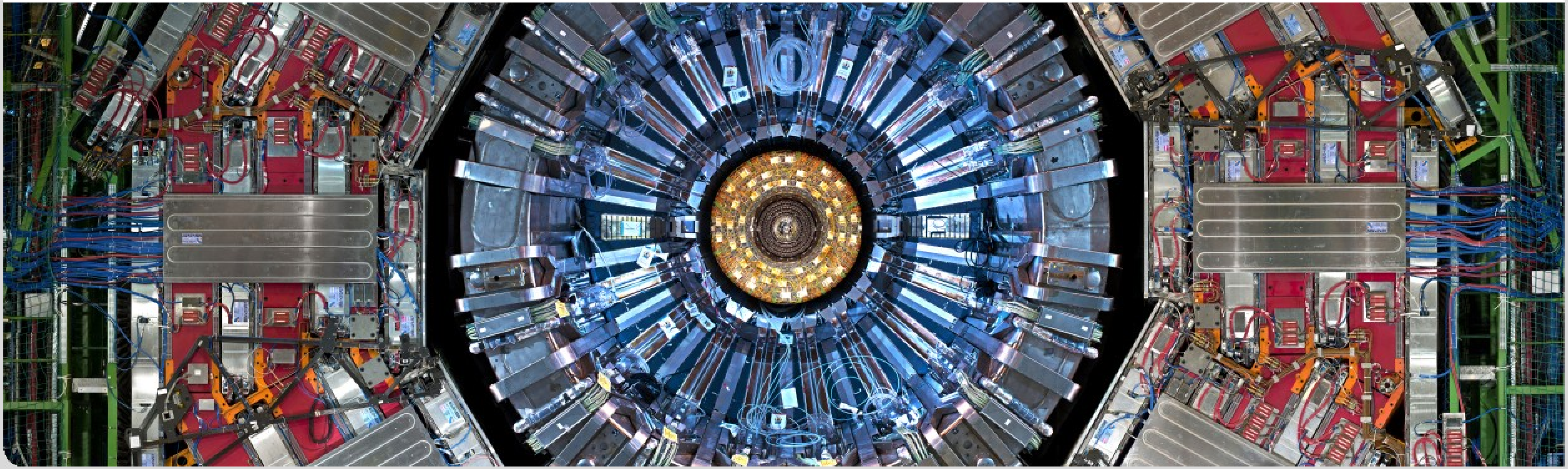
INSTITUT FÜR EXPERIMENTELLE KERNPHYSIK – DEPARTMENT OF PHYSICS



The CMS experiment at the LHC

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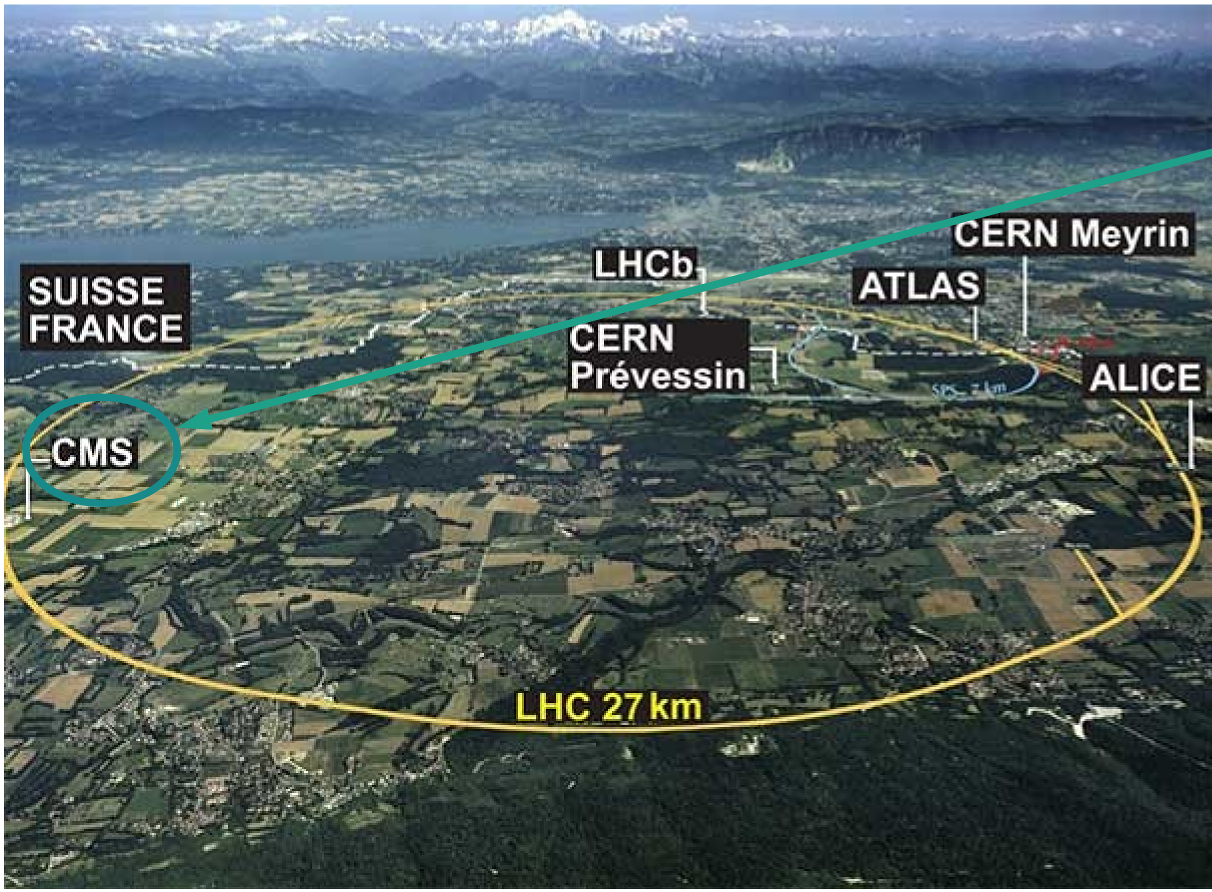
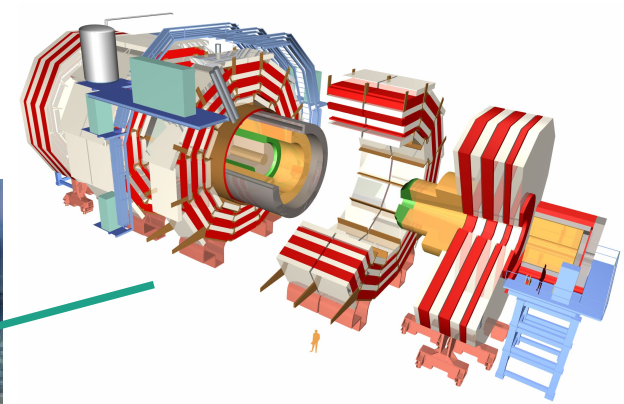
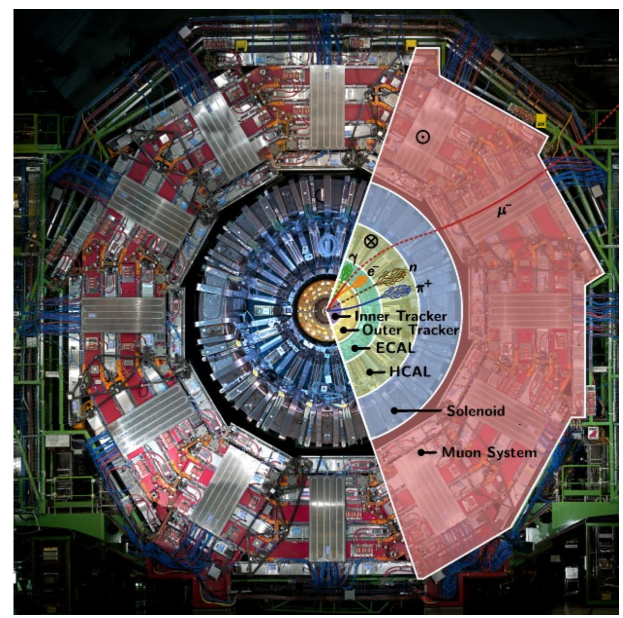
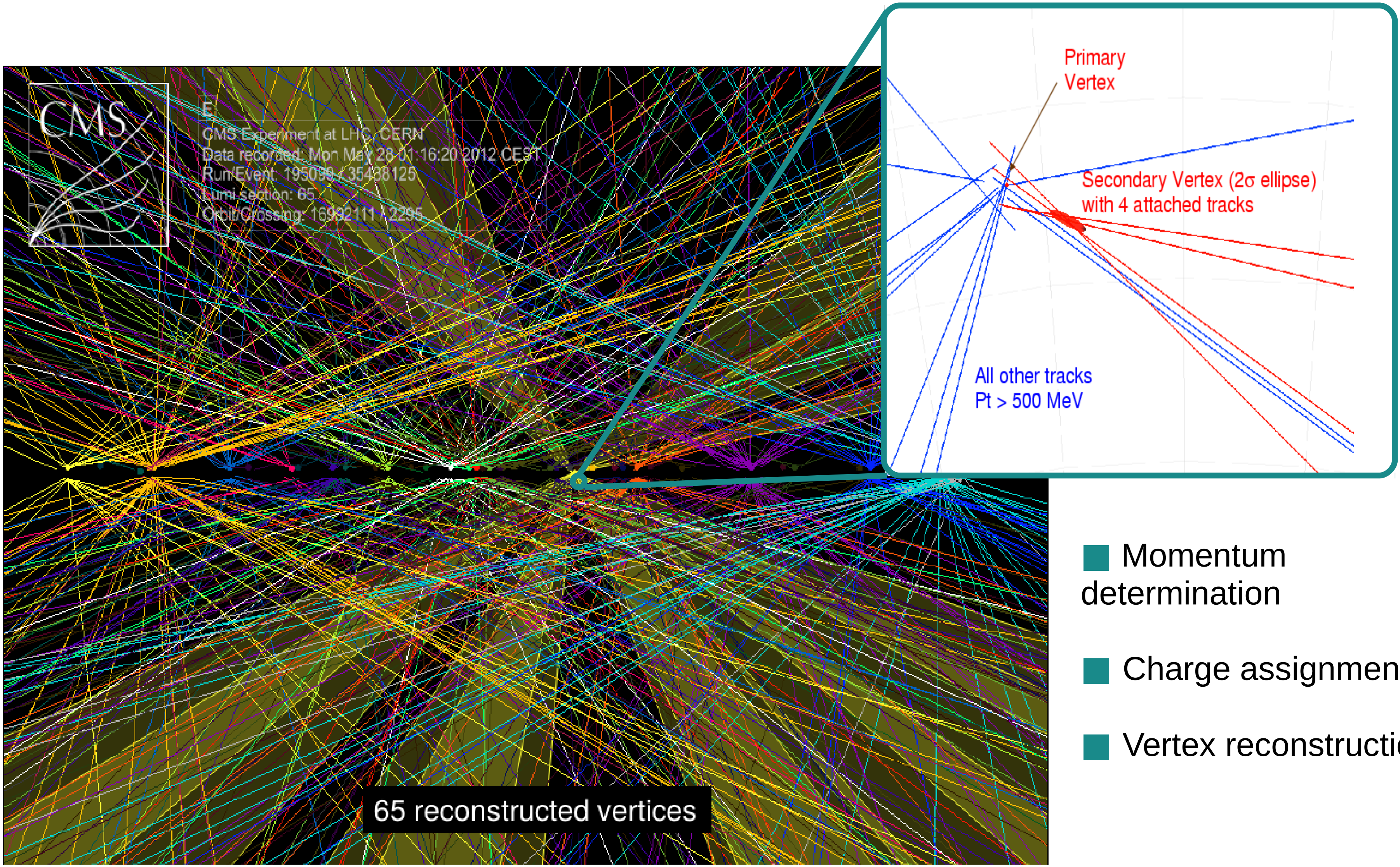
- LHC: **proton-proton collider** @13TeV (since spring 2015)
- Four major experiments: ATLAS, **CMS**, ALICE, LHCb







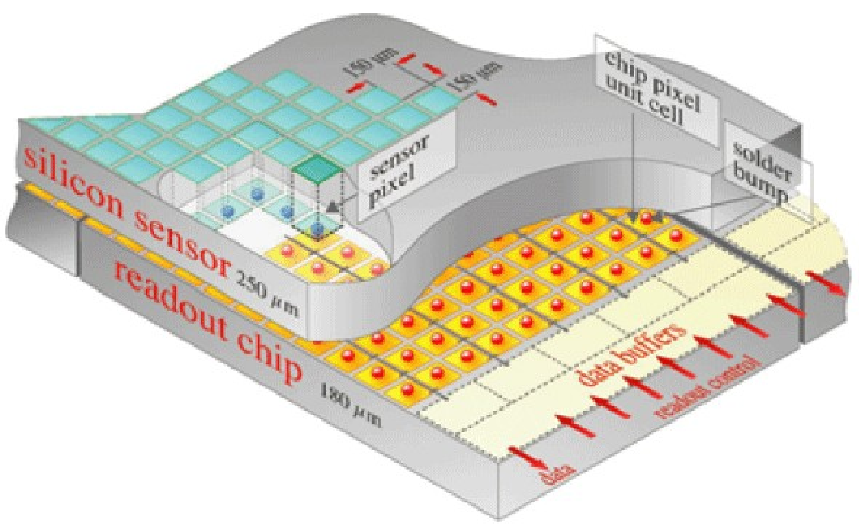
The importance of tracking

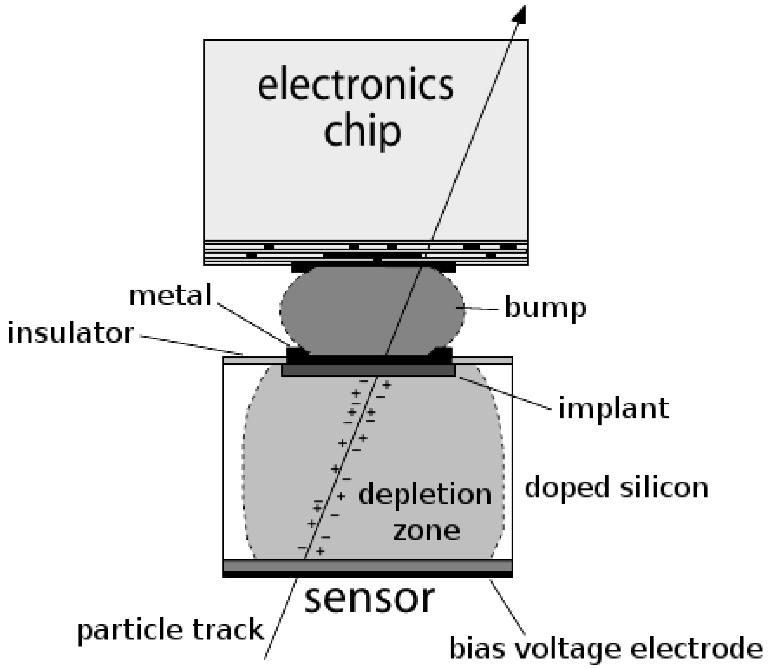


- Momentum determination
- Charge assignment
- Vertex reconstruction

Pixel detectors in a nutshell

- Create a **depletion zone** in a doped silicon sensor applying a reverse bias
- Interacting charged particles generate **electron/hole pairs**
- e/h drift in opposite directions under the applied field
- The **induced signal** is read out





Hybrid pixel detectors

- Each sensor cell is **mechanically** and **electrically** connected to the readout chip via tiny **solder bumps**

LHC Schedule

source: http://hilumilhc.web.cern.ch/about/hl-lhc-project

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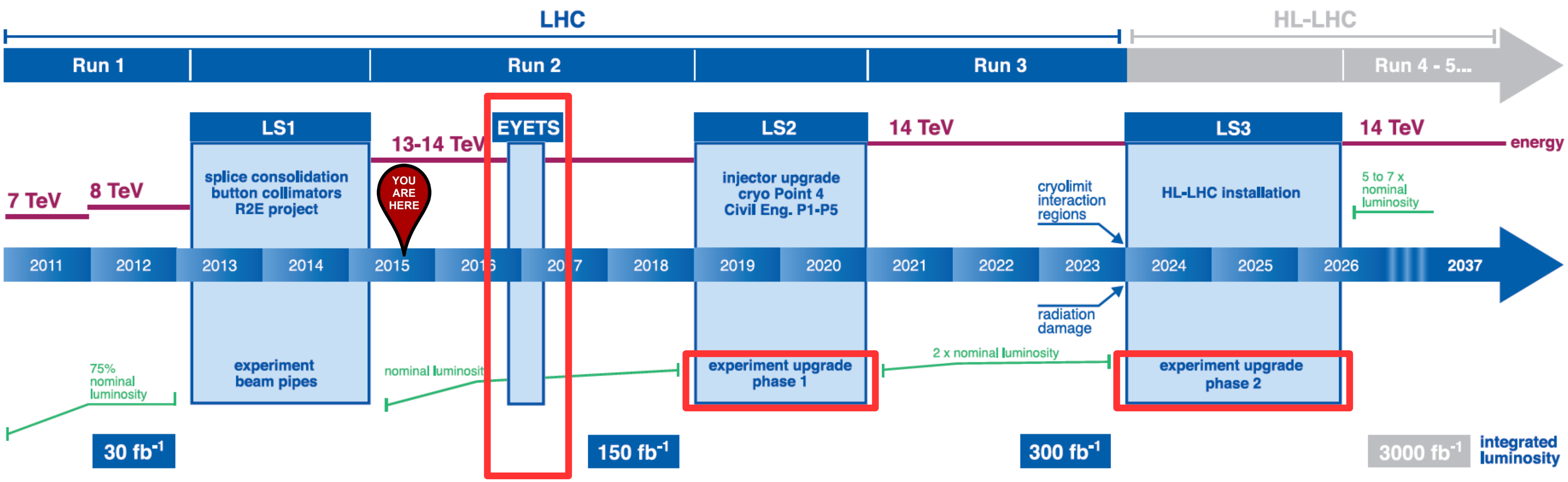


Keep the same detector performance ...in a (much) harsher environment

Two **upgrade phases** planned for all the LHC experiments

For the CMS tracker:

- **Phase 1**: exchange of the ***pixel detector*** (earlier, during 2016/17 **E**xtended **Y**ear **E**nd **T**echnical **S**top) → be ready to operate at twice the design luminosity

this talk

- **Phase 2**: complete ***renewal of silicon tracker*** (pixel + strips)

The CMS Pixel Phase 1 Upgrade

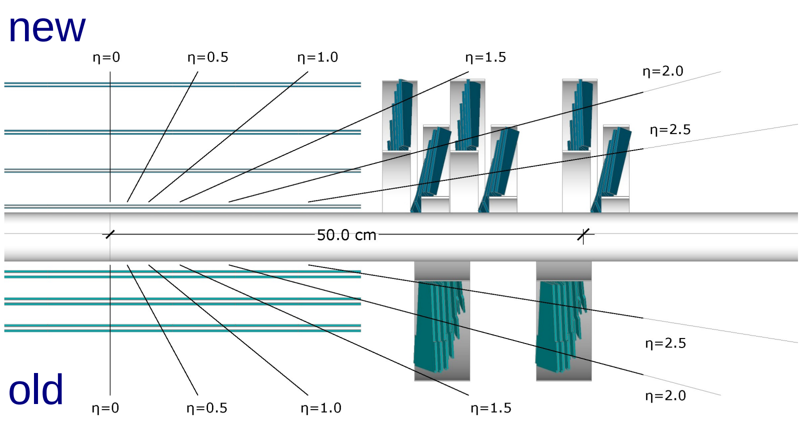
- **Four BPIX layers** and three FPIX disks per z-end
  → **4-hit coverage** up to |η| = 2.5
  → improve track reconstruction

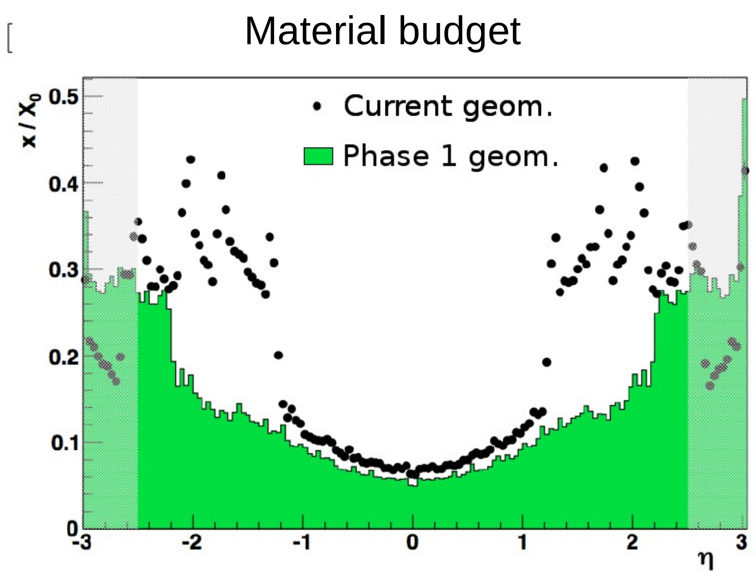
- **New mechanical structure** and new cooling system
  → **lower material budget**
  → less photon conversion and energy degradation

- **New readout chip** (ROC) design
  → **readuce dead time** in readout

Goal: improve tracking (higher efficiency, smaller fake rates), increase spatial resolution and b-tagging performance

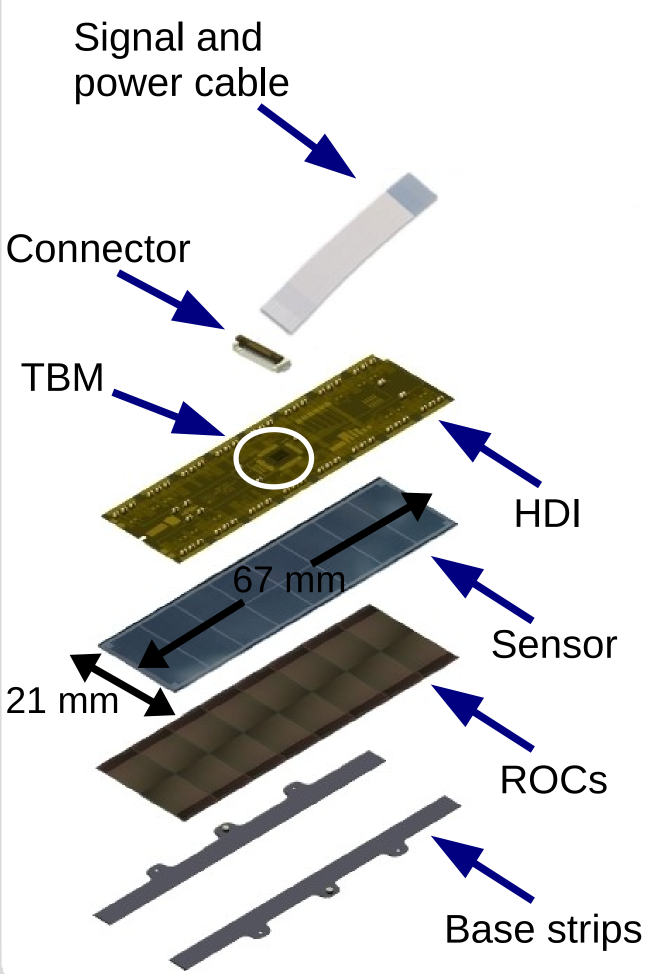
Production of new fourth barrel layer (R = 160 mm, 512 modules) is a joint effort of German institutes: KIT, DESY, U Hamburg, Aachen



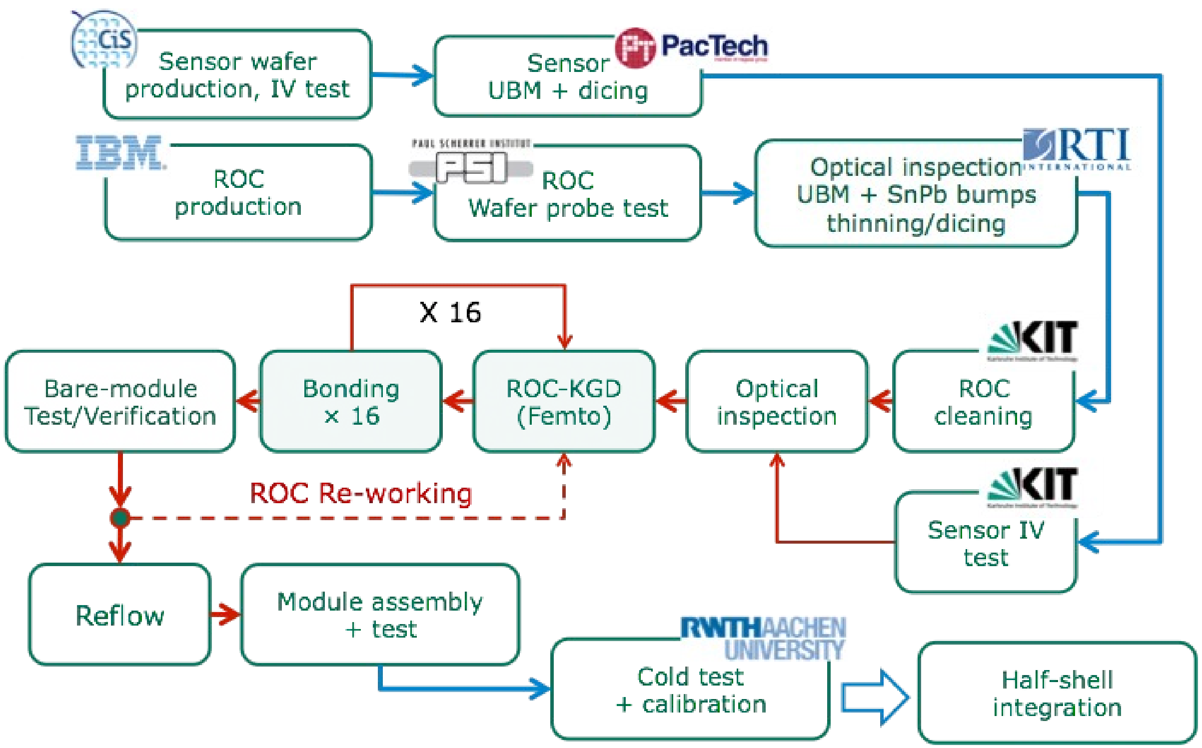


KIT Module Production and Testing Workflow

A **module** is the smallest subunit of the CMS pixel detector (16 ROC x 4160 = 66560 pixels)
Half of the modules for the 4th layer (+ spares) being produced and assembled at KIT



KIT/Aachen production workflow



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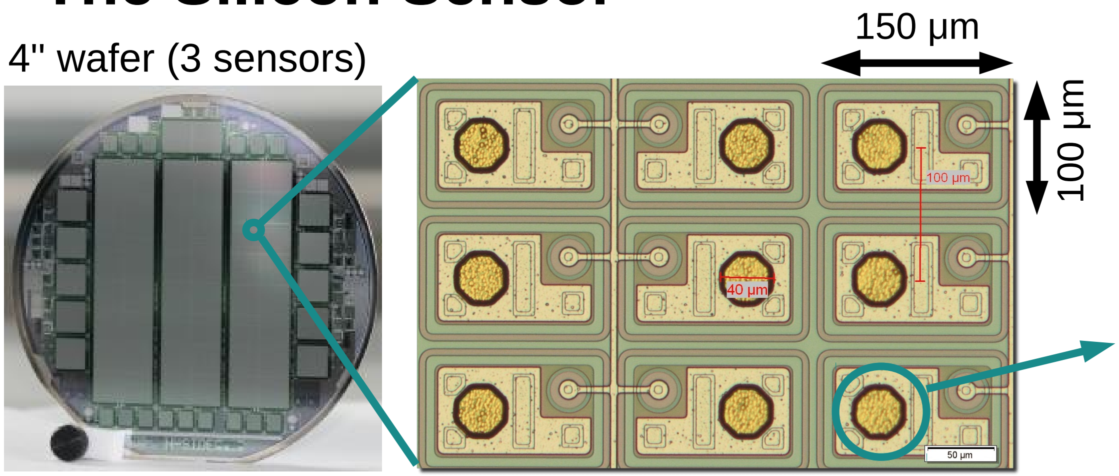
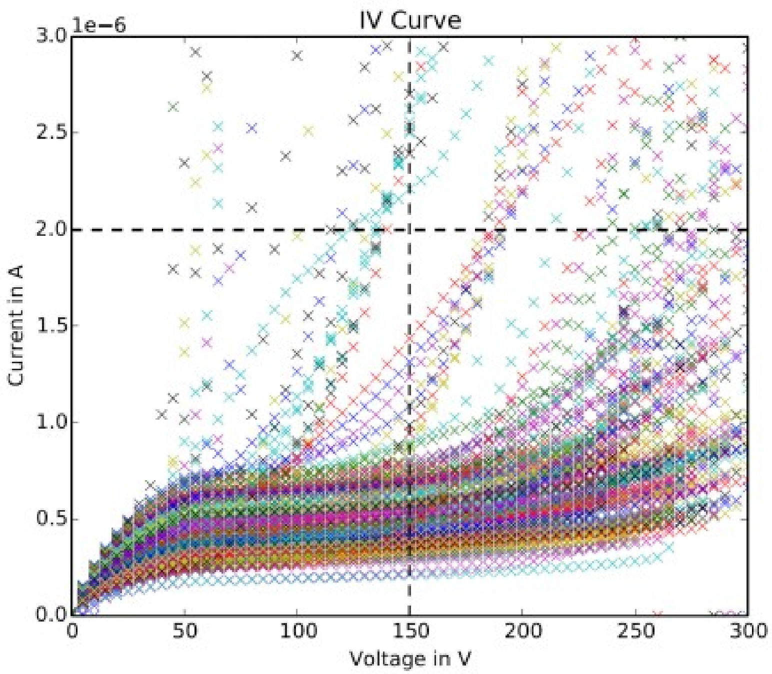
The Silicon Sensor

4" wafer (3 sensors)



66560 pixels on a 66.6 x 18.6 mm^2 area
n+ implants on a n-bulk with reverse bias

Under Bump Metallization (UBM) deposited on the opening pads of each pixel cell: needed for bump bonding process



After UBM deposition, dicing and shipping, an **acceptance test** performed at KIT for all the sensors: sensor characterization with I-V curve on probe-station

- I < 2 µA @ 150 V
- slope I (150 V) / I (100 V) < 2

Measured efficiency UBM deposition and dicing: >90%

After acceptance test: ***storage*** in inert atmosphere, ***optical inspection*** before bump bonding (cleaning if needed)

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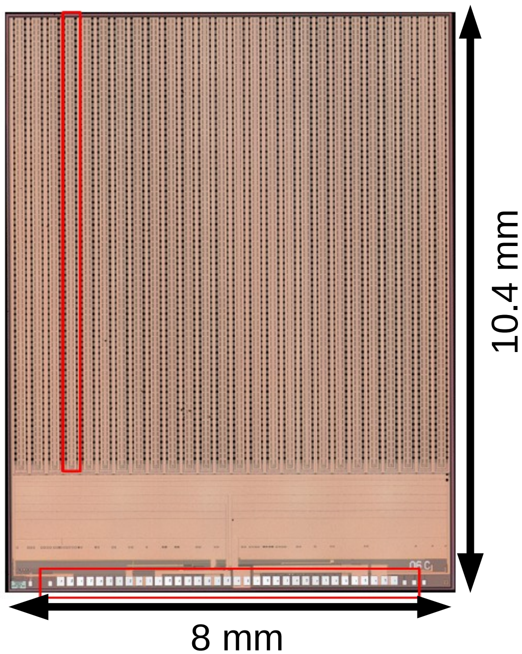
The Readout chips (ROCs)



10.4 x 8 mm^2 area: **52 x 80 pixel unit cells** matrix + chip periphery + 26 Al wirebond pads for readout

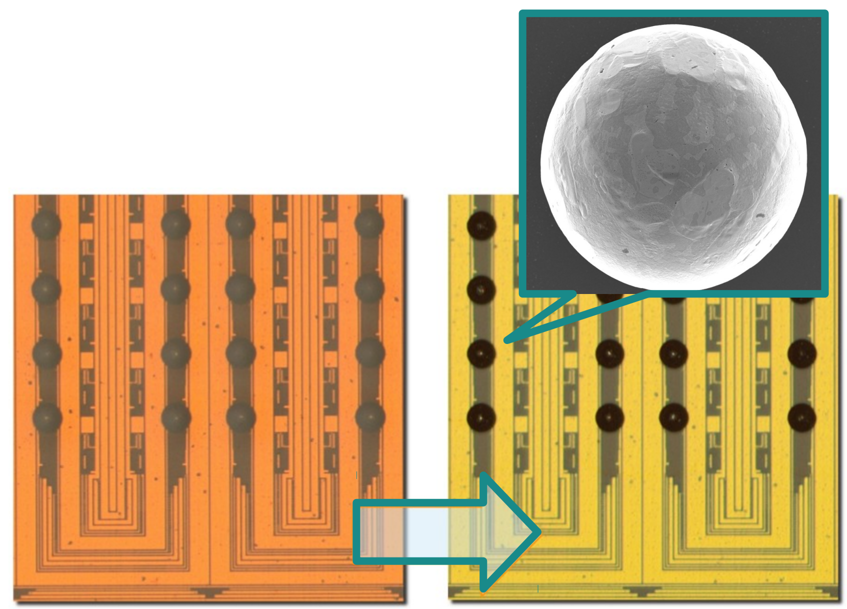
KIT strategy: rely on industry for bump deposition, perform flip-chip bonding between ROCs and sensor in-house

Bumping process:
- eutectic SnPb bumps on the ROC side
- thinning (~175 µm) and dicing at subcontractor

- received ROCs covered with thick photoresist layer for bump protection

- dedicated ***cleaning procedure*** with chemical solvents developed

- detailed (semi-automatized) ***optical inspection*** of all the bumps and selection of the best components before bonding



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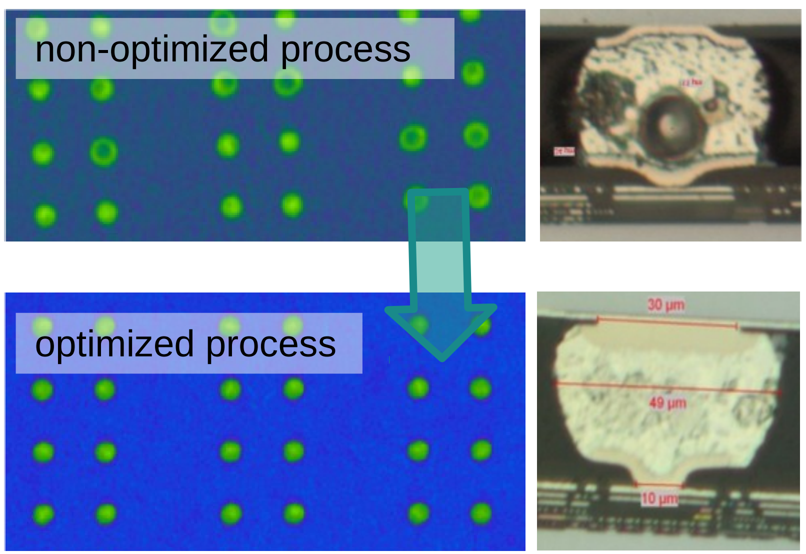
Bump bonding of CMS bare modules

Electrical and mechanical connection between sensor tile and 16 readout chips → "bare module"

Challenges:

- **extremely clean environment** needed (cleanroom)
- **micrometric precision** in sensor/ROC alignment and planarity

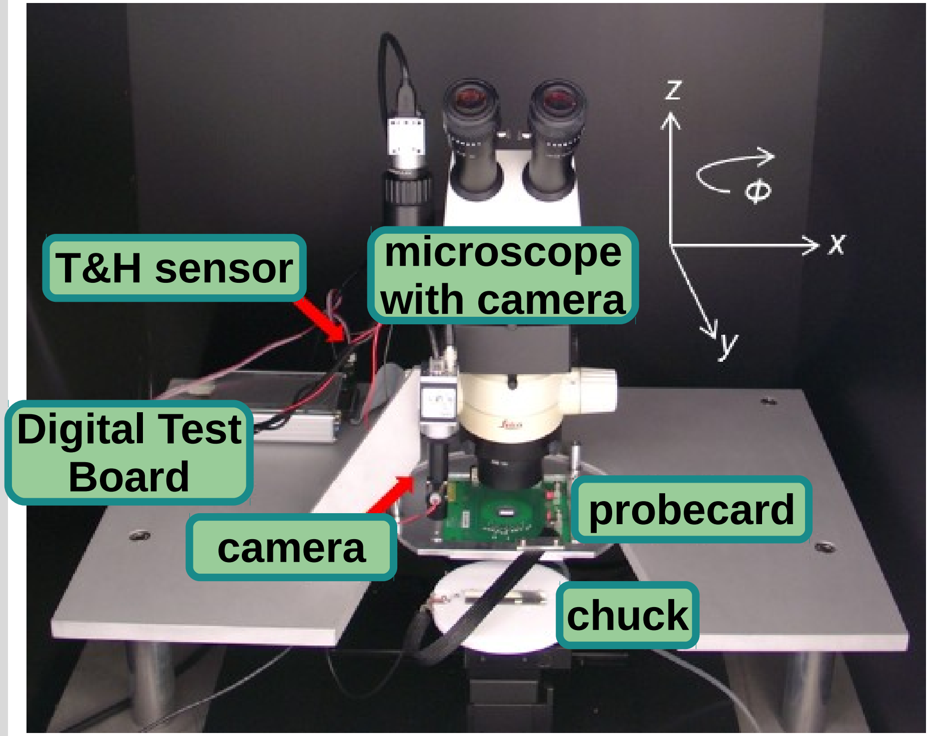


Quality tests:

- ***cross-section*** of bonded assemblies
- destructive ***pull-test***
- scanning ***laser metrology***
- micro ***x-ray scan*** (external)

Process parameters tuned and optimized

Bare Module Testing



Probe the **quality of the bump connection** between sensor and ROCs

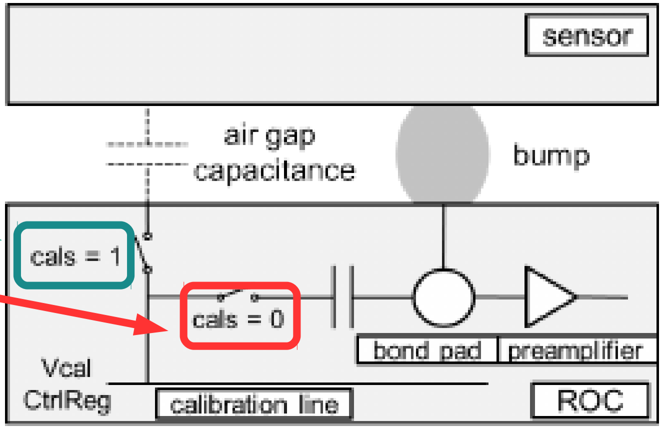
Custom **probe-station** designed and built at KIT

- probecard w/ needles to contact the wirebond pads on each ROC
- module placed on dielectric chuck
- motorized table (x/y/z/phi) for alignment

In case of problems localized on specific ROCs **reworking** of the bare module **is possible**

- find **dead pixels** and pixels with **missing bumps**

- inject the signal capacitatively into the sensor
- inject the signal directly into the ROC preamp.



Challenges: **keep the noise level** during the test **as low as possible**

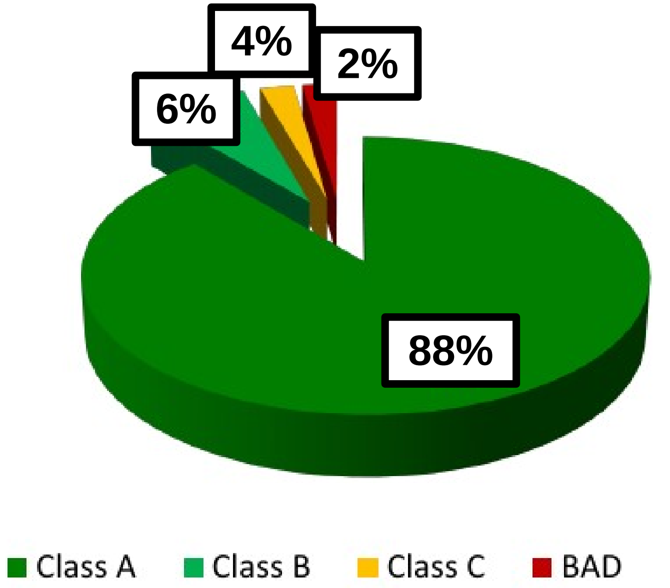
Bare Modules: some production statistics

After testing bare modules are **graded based on the worst of a set of criteria**:

- sensor leakage current
- digital current of each ROC
- number of defective pixel channels

→ class **A**, **B** (equipped as full modules)
class **C**

First results from KIT production (ongoing)

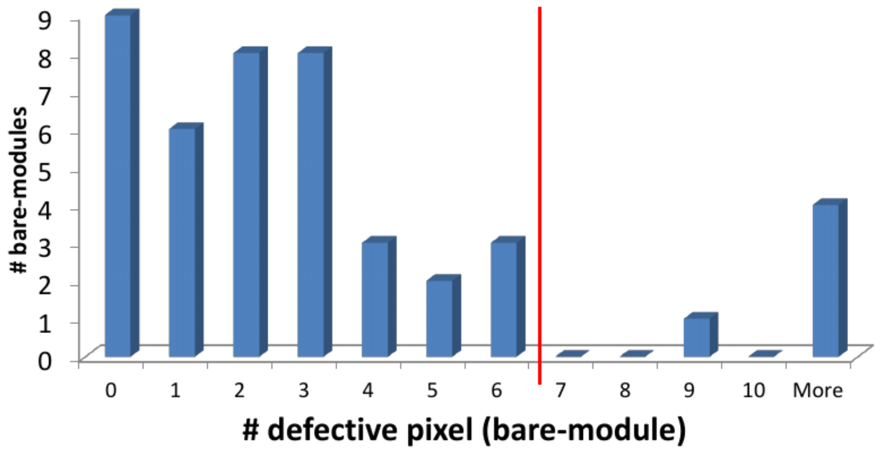


49 (+1) production bare modules assembled so far

- **44 class A**
- **3 class B**

} **94%**

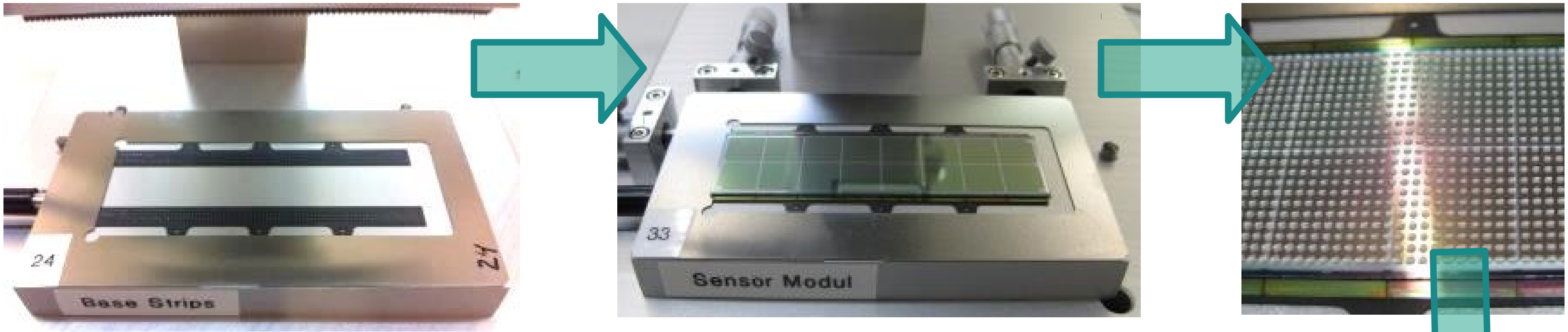
- **2 class C** (+ **1 lost**)



majority of class A bare modules with
less than 0.009% defective pixels/module

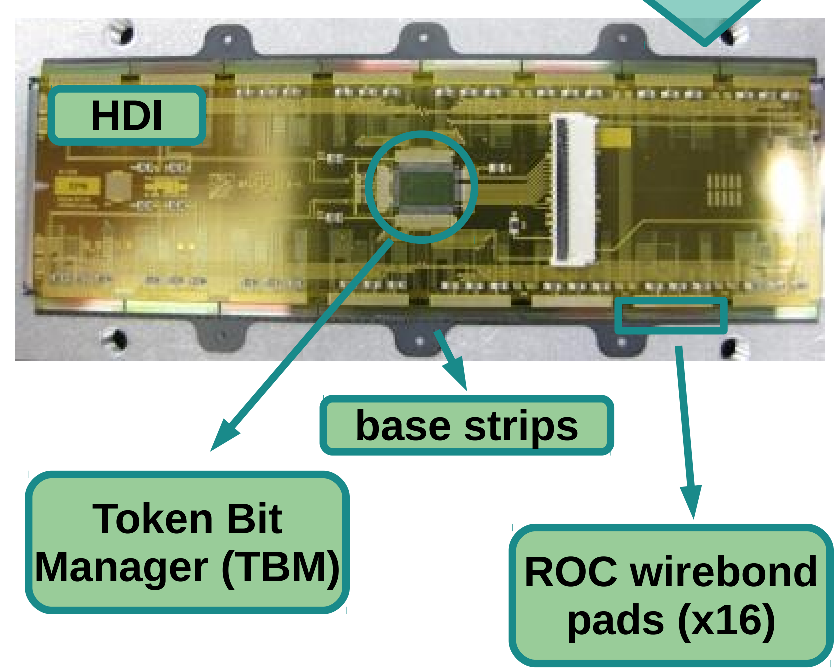
Detailed scrutiny in acceptance tests pays off!

Module assembly line



Assembly line fully operational in large class 100000 cleanroom

- set of **gluing station**
  - TBM on HDI
  - bare module on base strips
  - HDI + TBM on bare module
- movable microscope + camera for **process monitoring**
- coordinate measuring machine for **quality control**



Module assembly line

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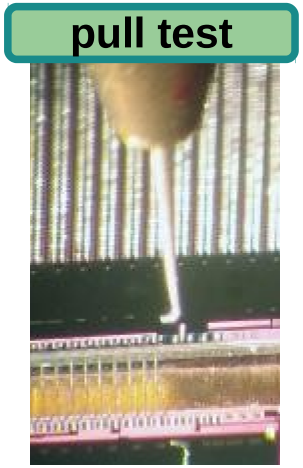
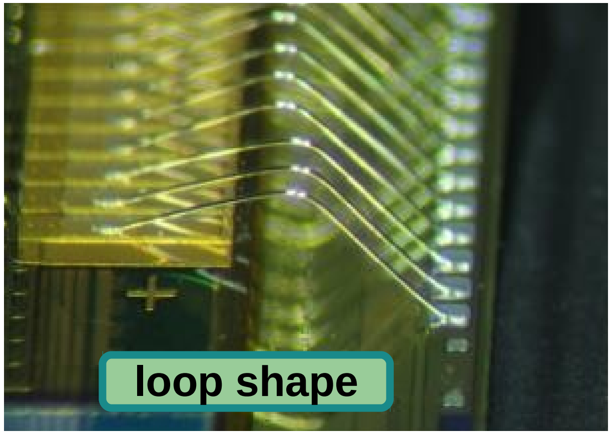
Wirebonding

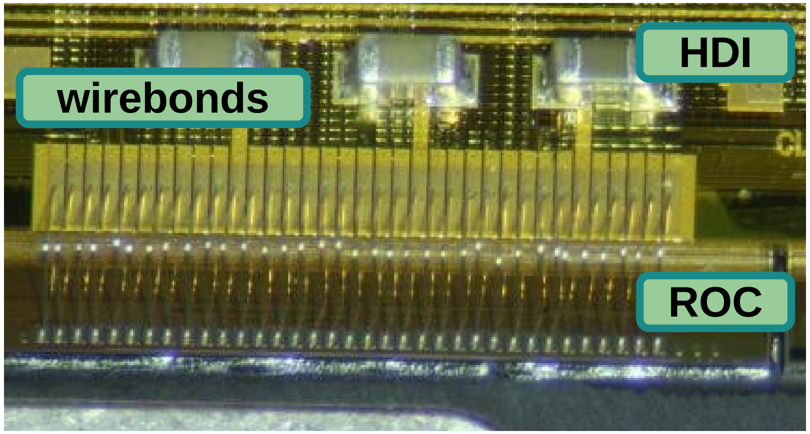
- connect the wirebond pads on each ROC to HDI
- **ultrasonic welding** with 25 µm wires

- process parameters optimized
- quality of the process assessed via ***optical inspection*** and ***pull-test*** of the single bonds

Very good pull strength achieved: > 10 g / bond







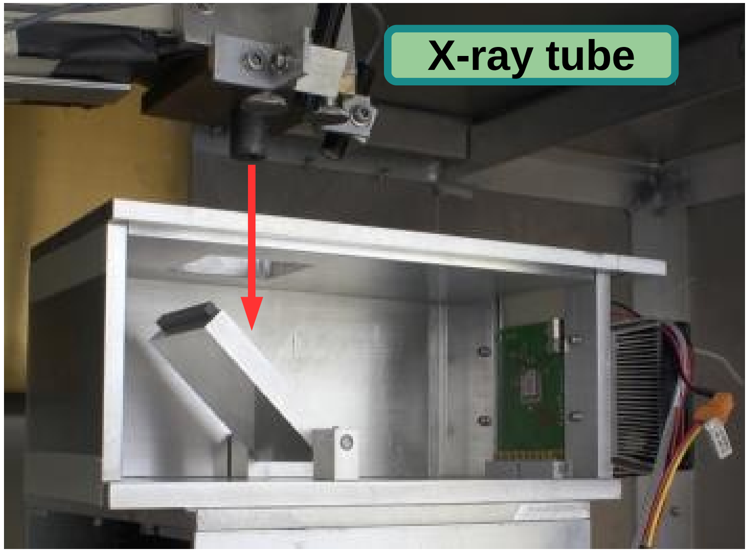
Module qualification at KIT

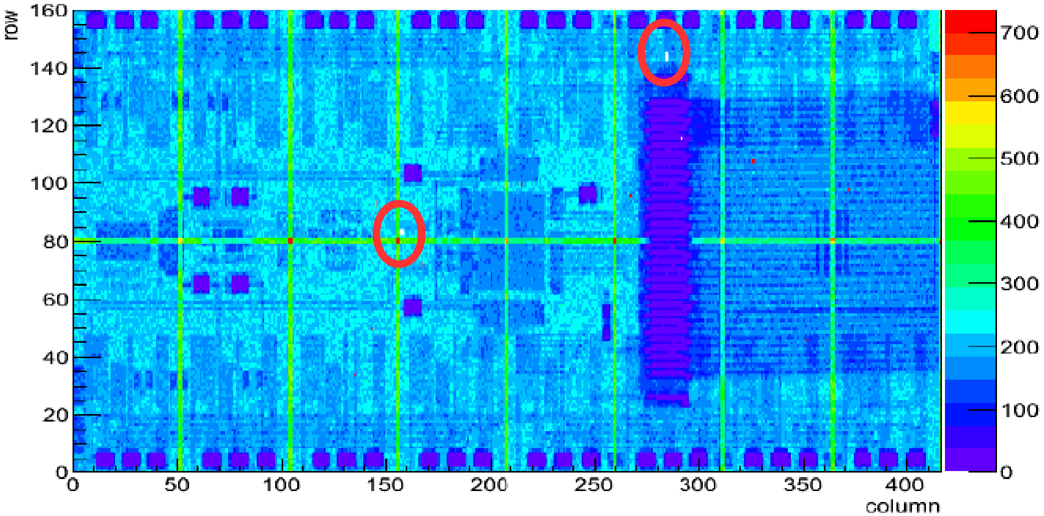
Full module qualification (and calibration) of KIT modules performed at RWTH Aachen

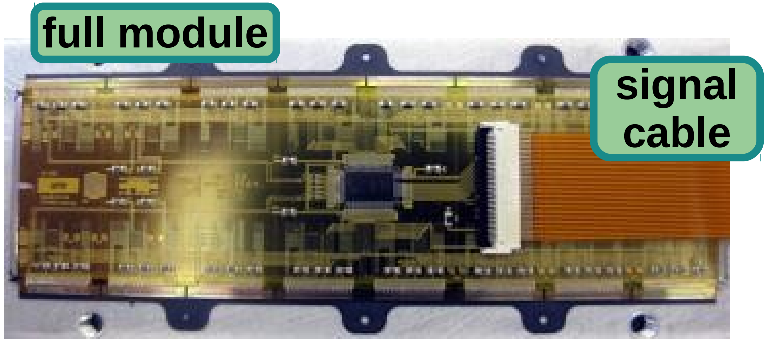
Basic checks @KIT before shipment
x-ray irradiation and ***hitmap***

- check the overall behaviour of the module
- reworking at this point is not possible anymore

Module placed in primary x-ray beam







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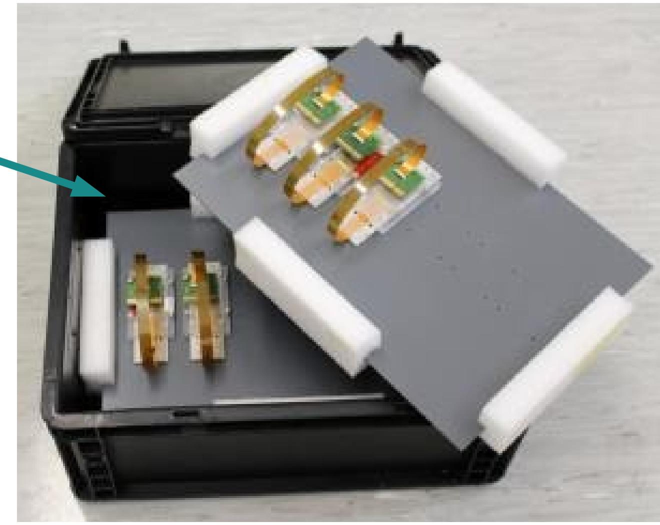
Module transport

Full modules placed in **ESD safe boxes**
(up to 18 modules per box)

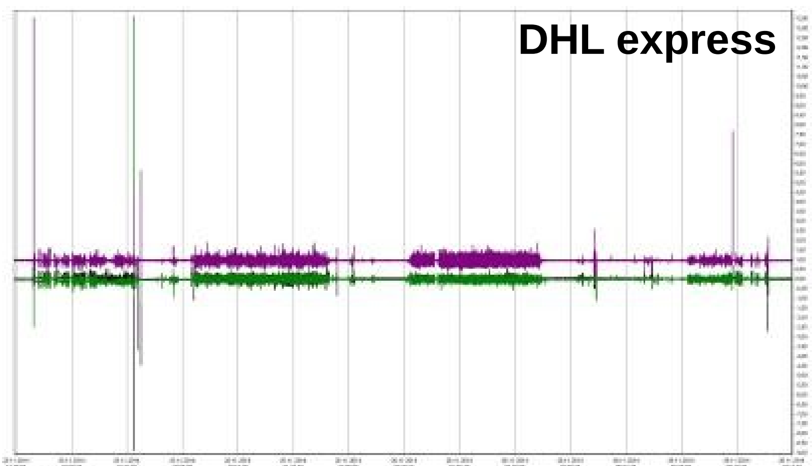
→ shipment to RWTH Aachen

Different transportation methods are possible:

- **Parcel service**: cheap but risk to damage the content due to bad handling
- Door-to-door **car courier service**: more expensive (factor 6!) but safer

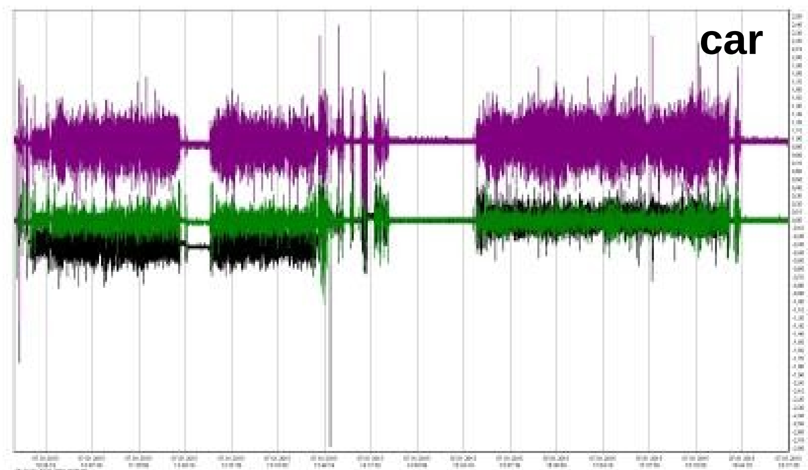


Accelerometer logger values



13 g

0 g



2 g

0 g

Data analysis and bookkeping

Data coming from the different production steps

- grading
- IV curves
- calibration results
- …

analyzed using **software common to all the production centers**

Results are uploaded to a **central DB** for bookkeping and information sharing

Mod ID	Built By	Status	Center	FullQual
	kit	INSTOCK		
M4564	KIT	INSTOCK	AACHEN	A
M4565	KIT	INSTOCK	AACHEN	A
M4566	KIT	INSTOCK	AACHEN	A
M4567	KIT	INSTOCK	AACHEN	A
M4568	KIT	INSTOCK	AACHEN	A
M4570	KIT	INSTOCK	AACHEN	A
M4571	KIT	INSTOCK	AACHEN	A
M4573	KIT	INSTOCK	AACHEN	A
M4574	KIT	INSTOCK	AACHEN	A
M4576	KIT	INSTOCK	AACHEN	A
M4554	KIT	INSTOCK	AACHEN	B
M4563	KIT	INSTOCK	AACHEN	B
M4569	KIT	INSTOCK	AACHEN	B
M4572	KIT	INSTOCK	AACHEN	B
M4550	KIT	INSTOCK	AACHEN	C
M4555	KIT	INSTOCK	AACHEN	C

production center **current location** **final grade**

\+ many more additional informations...

Summary and Conclusions

- LHC luminosity expected to increase in the next years: the pixel detector needs to cope with that → **full replacement at the end of 2016** (Phase 1 Upgrade)

- Production of new pixel modules shared among different institutes
- **KIT** responsible for building **half of the modules for the new fourth barrel layer**

- Real module production started in June 2015, expected to progress steadily until the beginning of next year

- **First results show a very high quality**