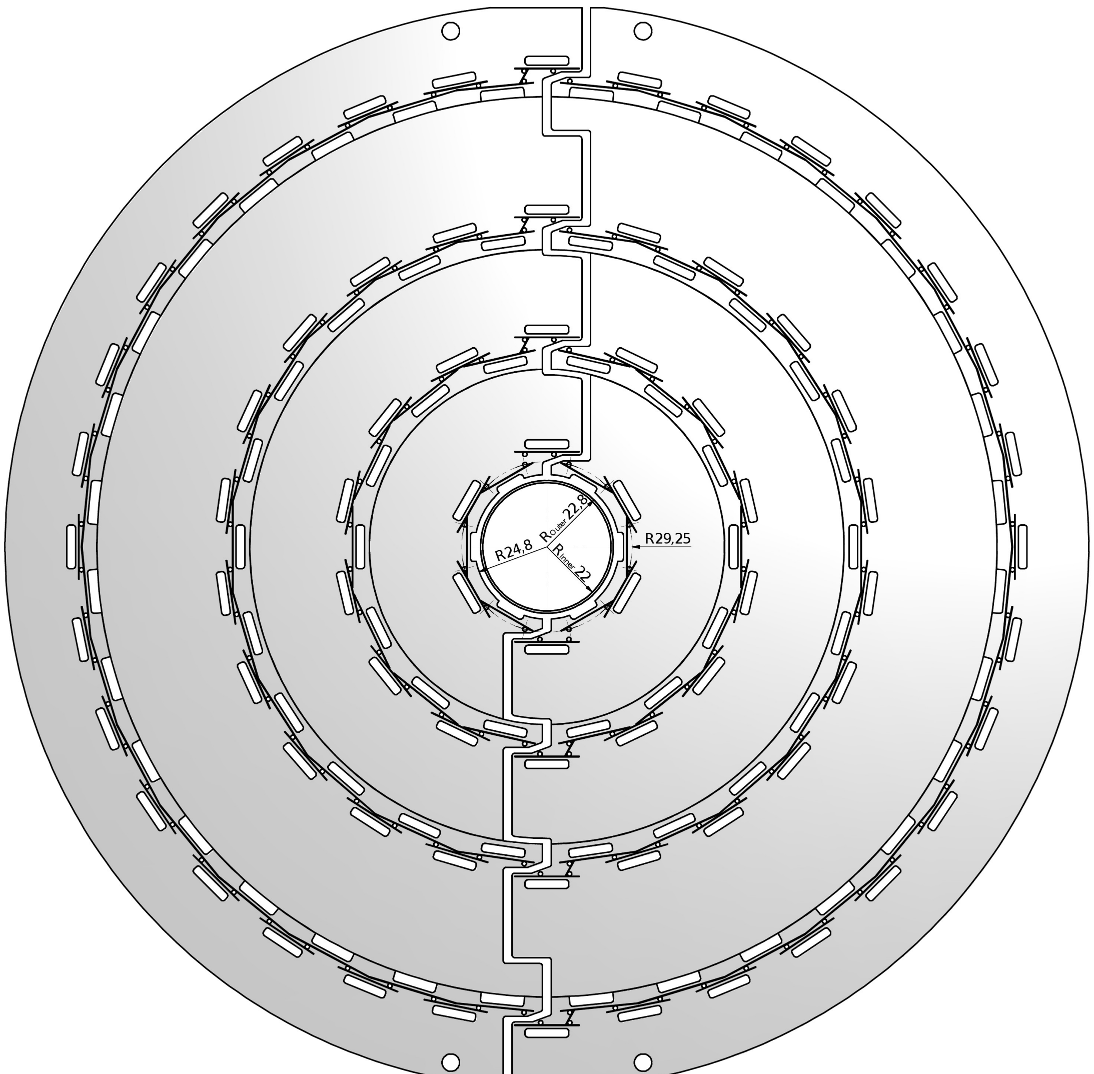
CMS Pixel Detector Upgrade

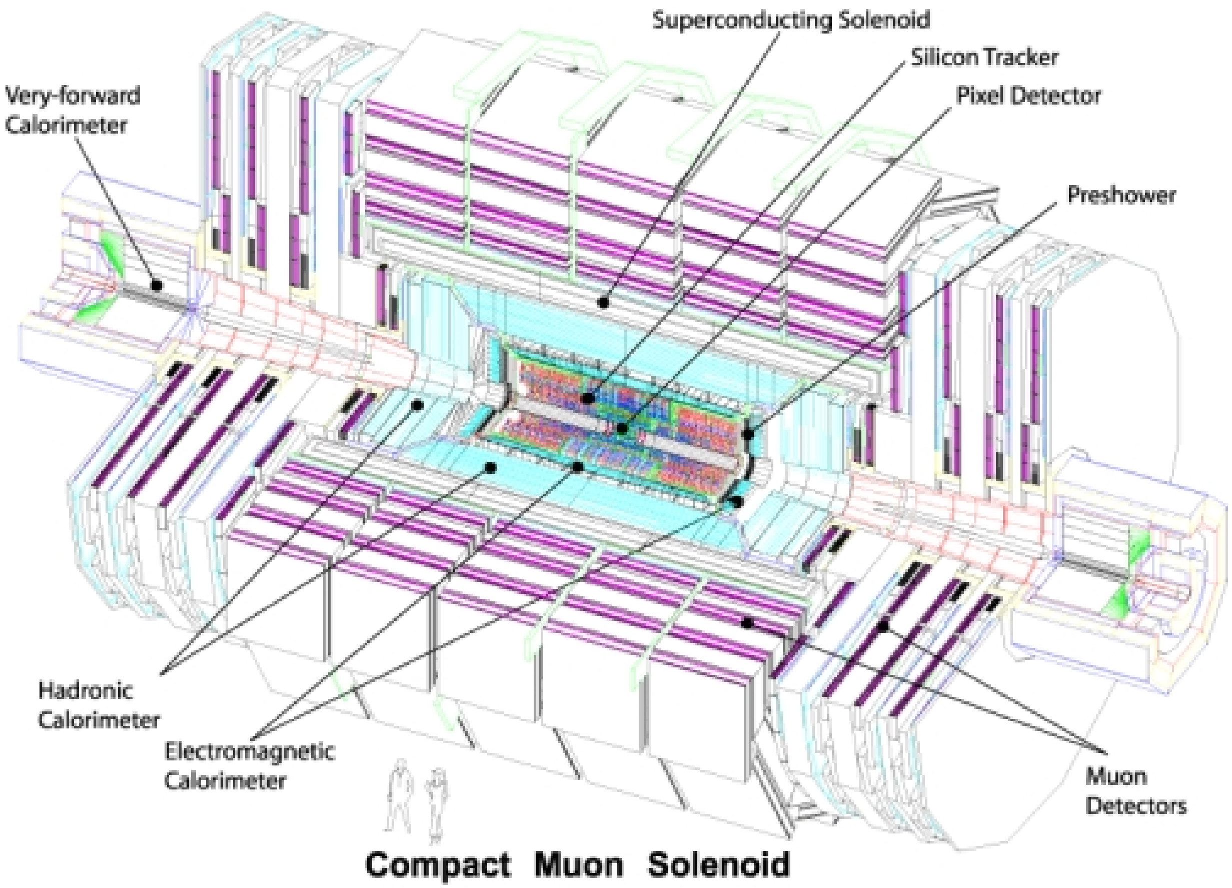
Daniel Pitzl, DESY

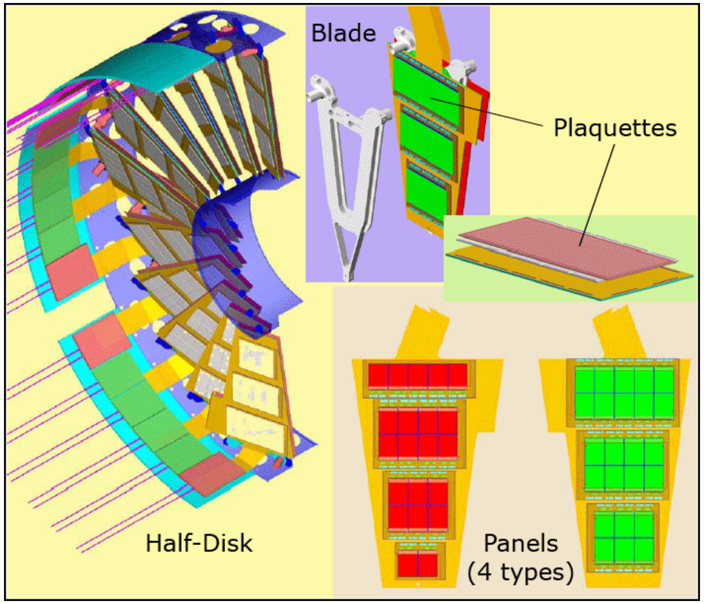
4th Alliance Detector Workshop 16.3.2011



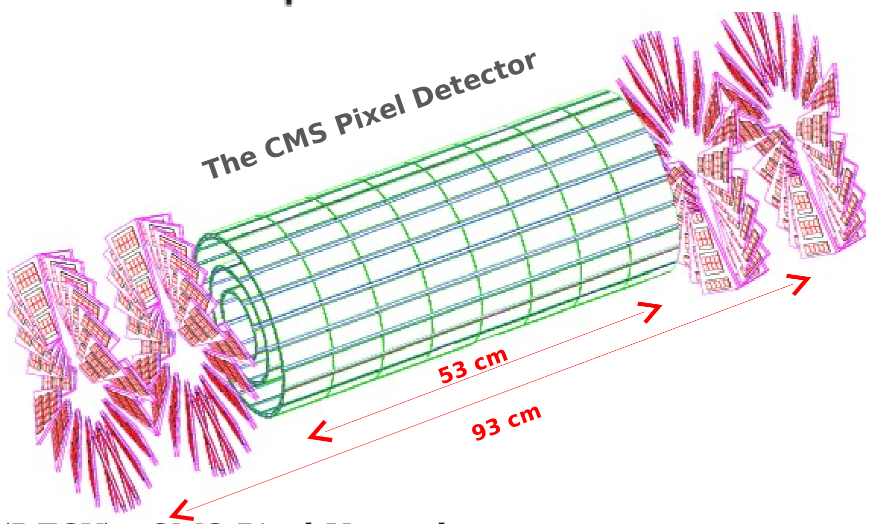
- Present pixel detector
- Material budget
- 4-layer upgrade
- Read out chip modifications
- Module assembly and testing

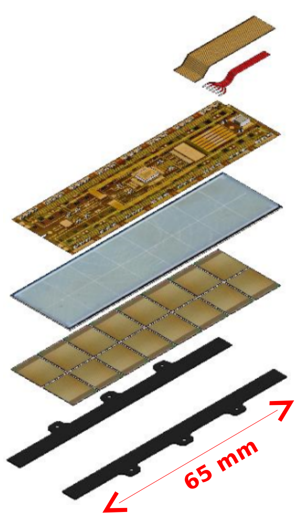
CMS and its pixel detectors





Panels of the Forward Pixel Detector



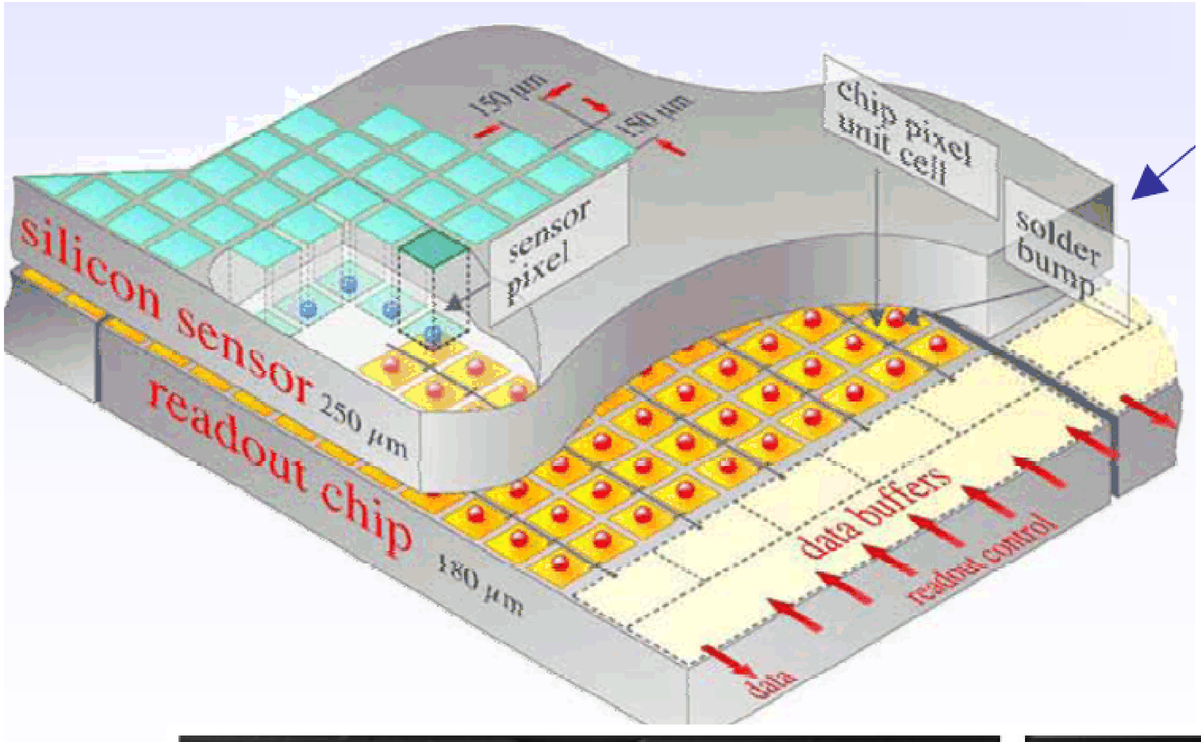


Forward Pixel Detector has 2 disks on each side at z = 34.5 cm and 46.5 cm.
FPix has 672 modules.

Barrel Pixel Detector has 3 layers at R = 4.4 cm, 7.3 cm, and 10.2 cm.
BPix has 768 modules.

Total of ~15,840 readout chips, 66M pixels.

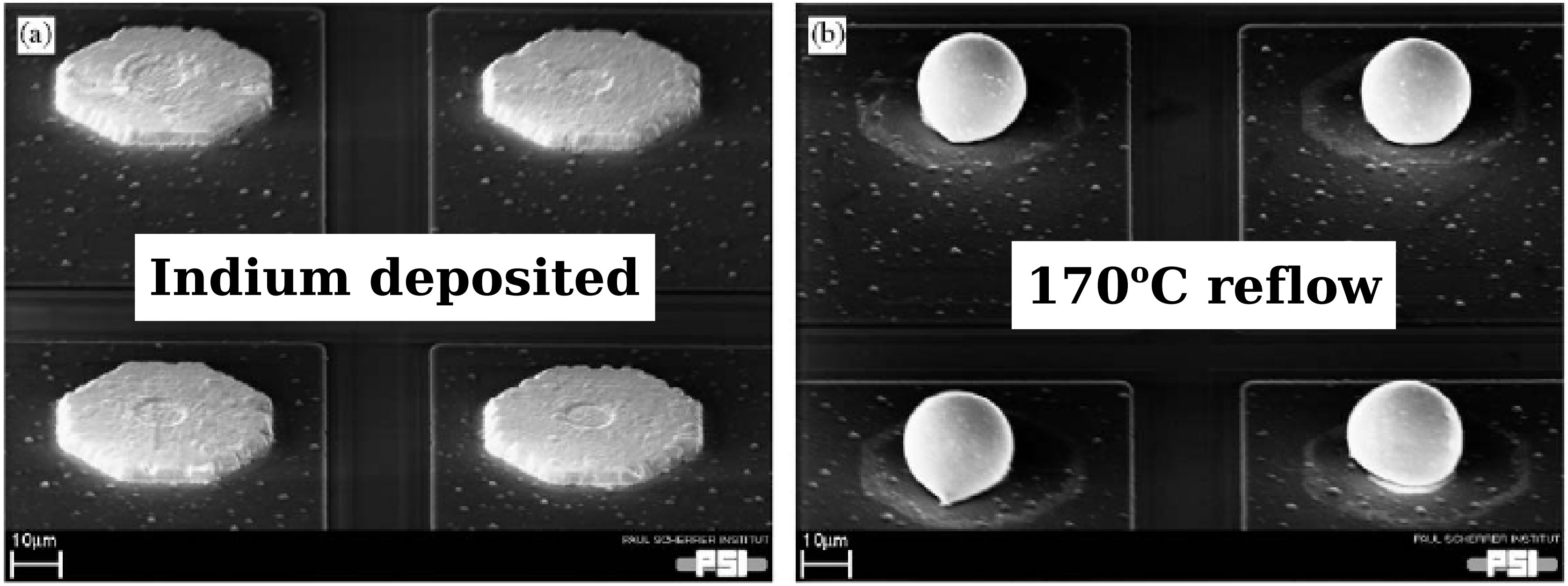
pixel sensor and readout chip



Hybrid pixel technology:
Silicon sensors
bump bonded to
CMOS readout chips.

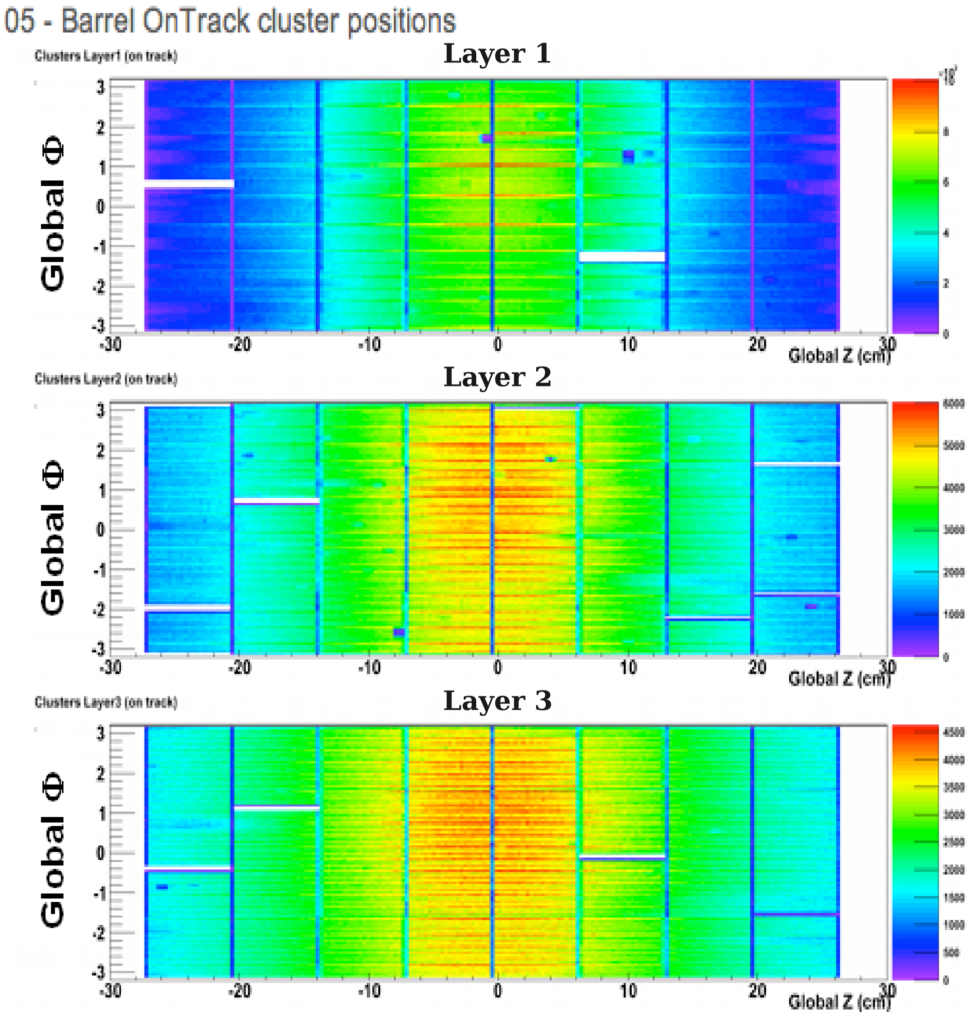
25 µm bumps placed
with 3 µm accuracy.

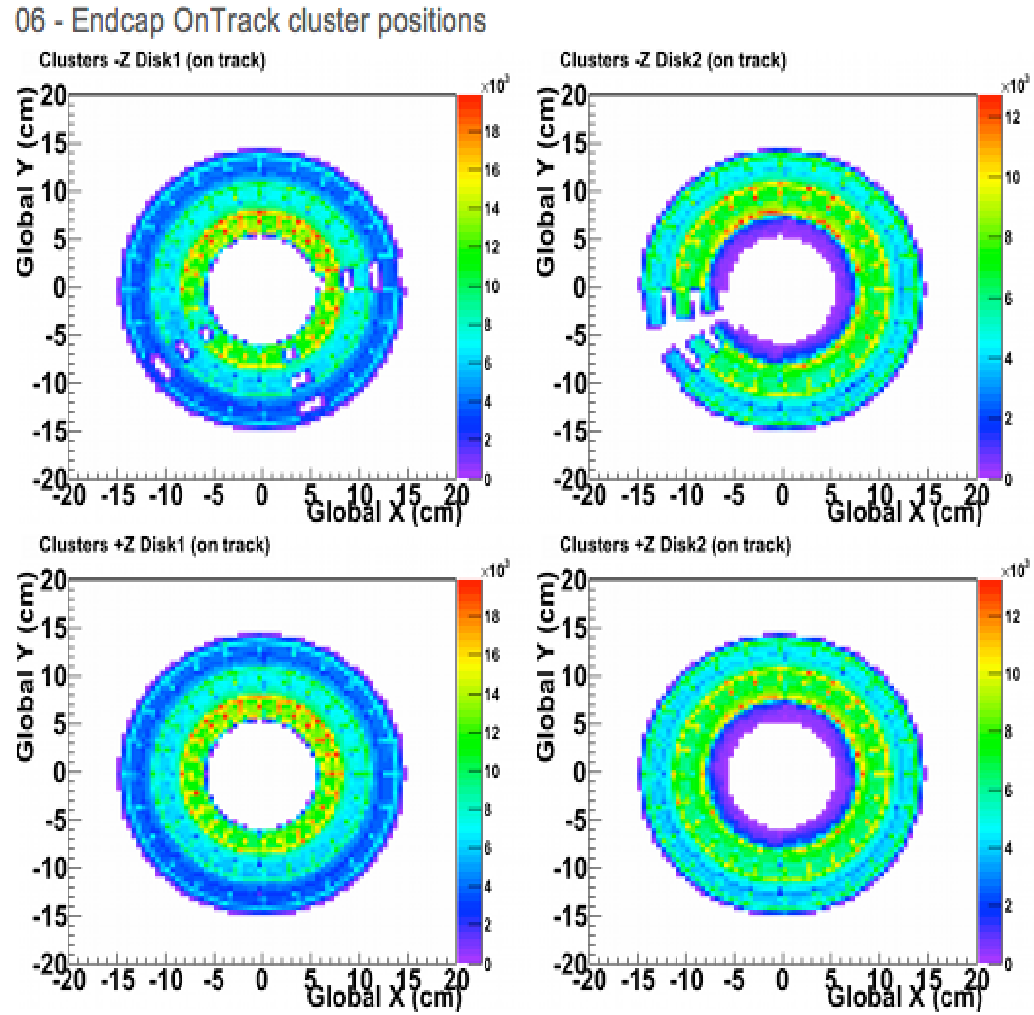
Cost driver: 2c/bump.



Pixel operation in 2010

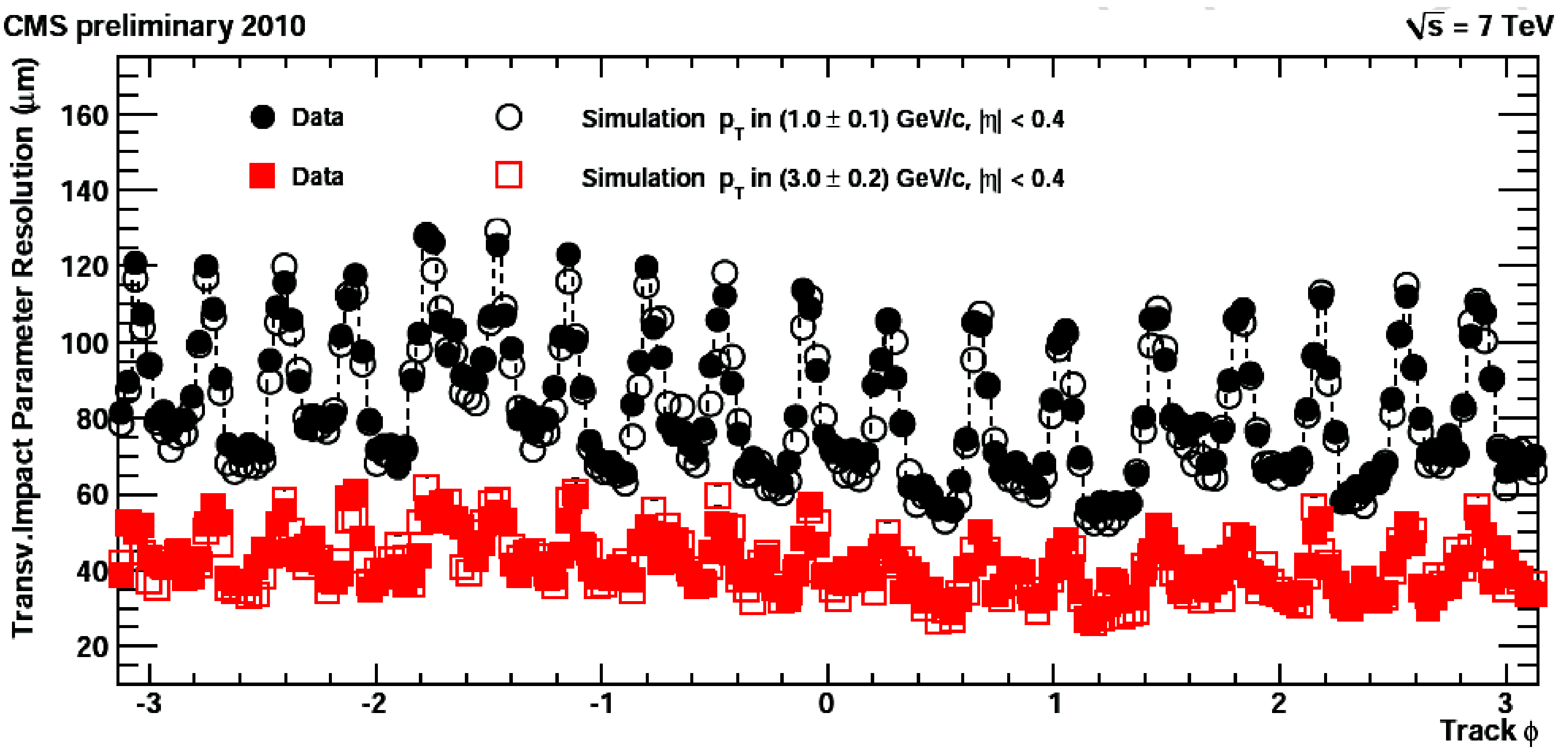
- 98.7% alive barrel modules.
- 96.4% alive forward modules.





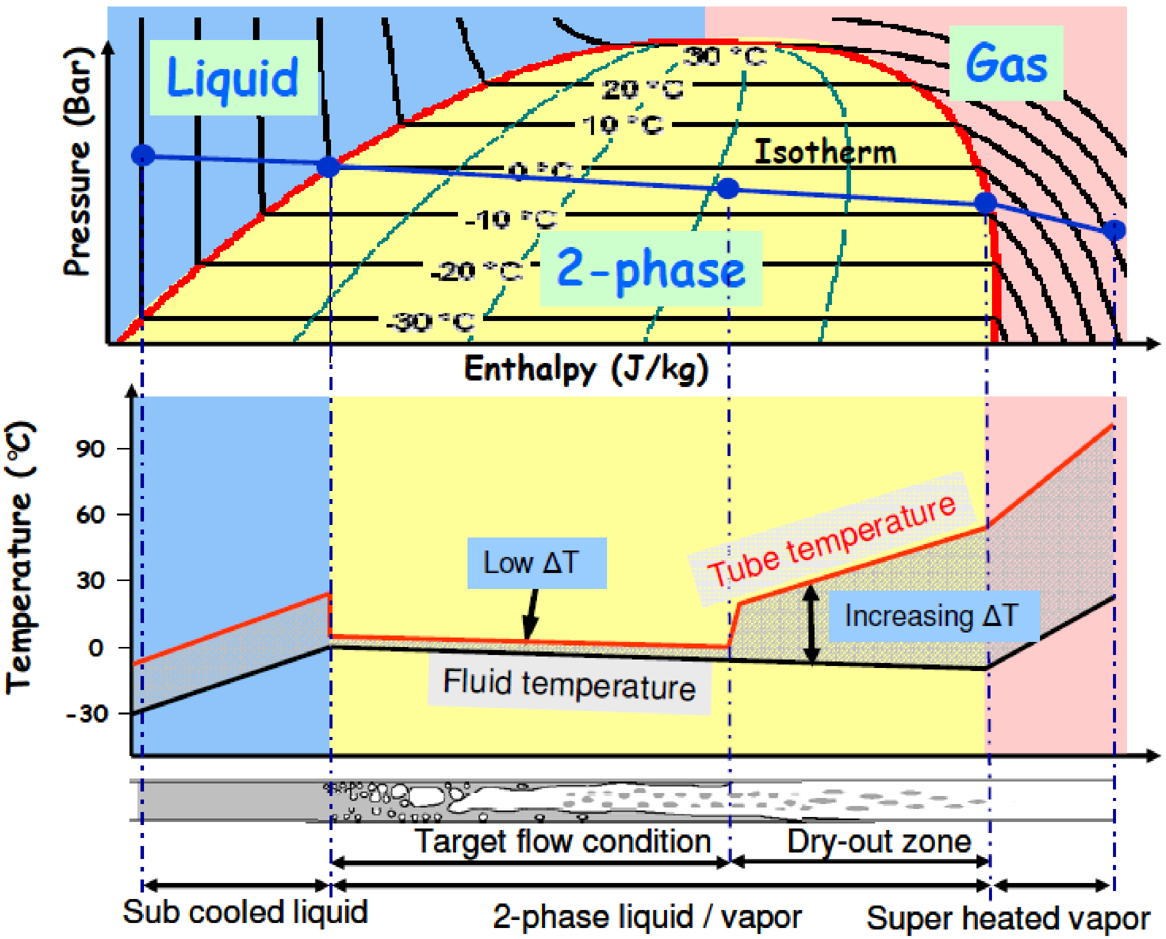
status Aug 2010

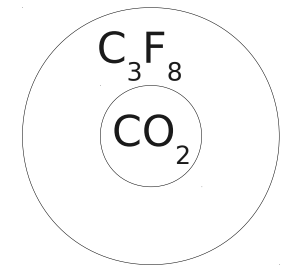
CMS impact parameter resolution

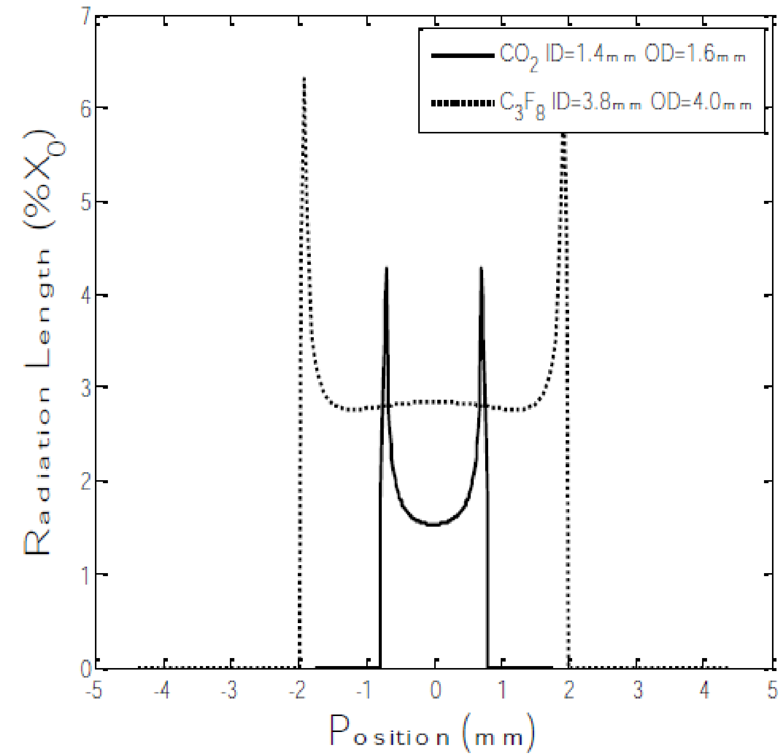


- 18-fold ϕ structure due to pixel cooling pipes visible at low p_T.
- Well described by the detector simulation.

Upgrade: CO_2 cooling



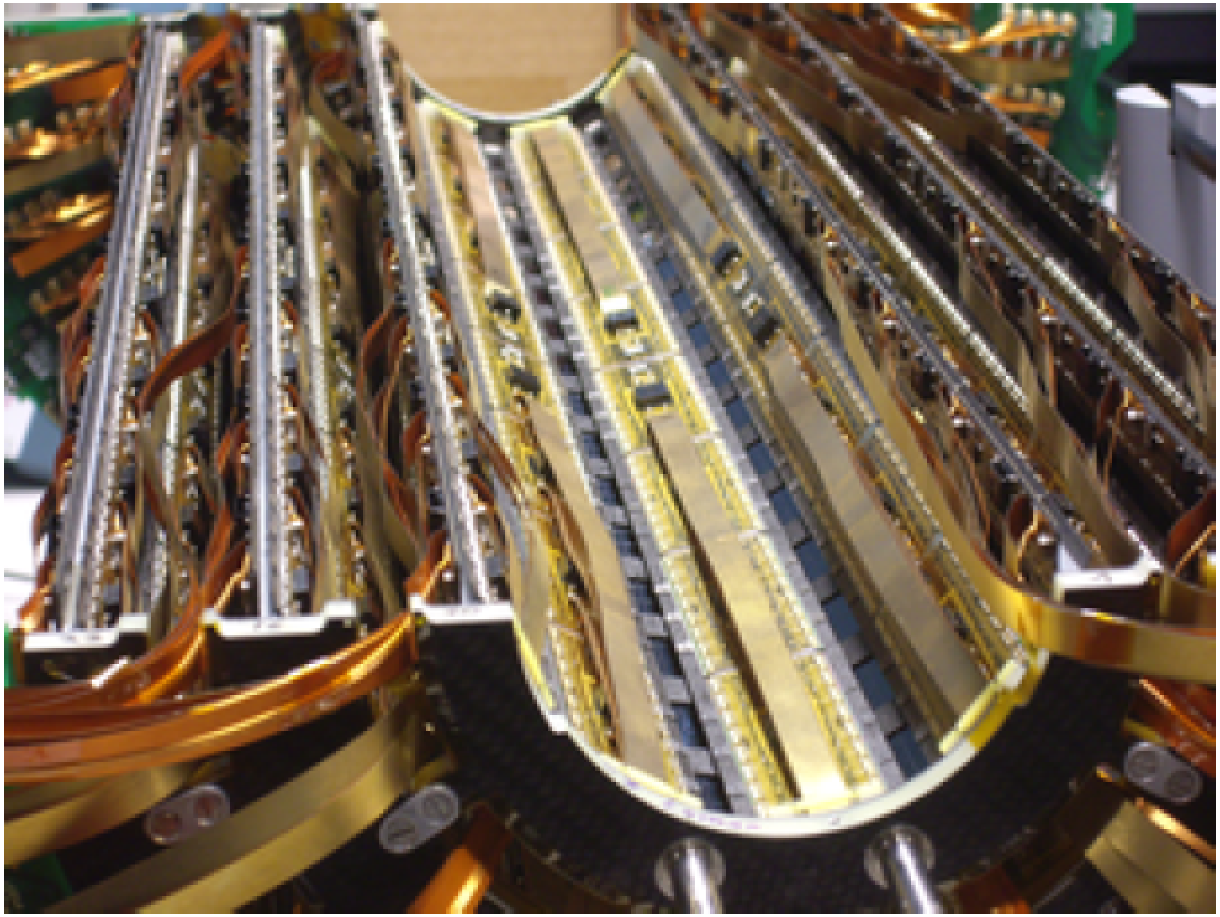




- 2-phase CO_2 cooling: large latent heat
- operating at -35°C, good viscosity
- reduces Si leakage current
- reduces defect activation in Si

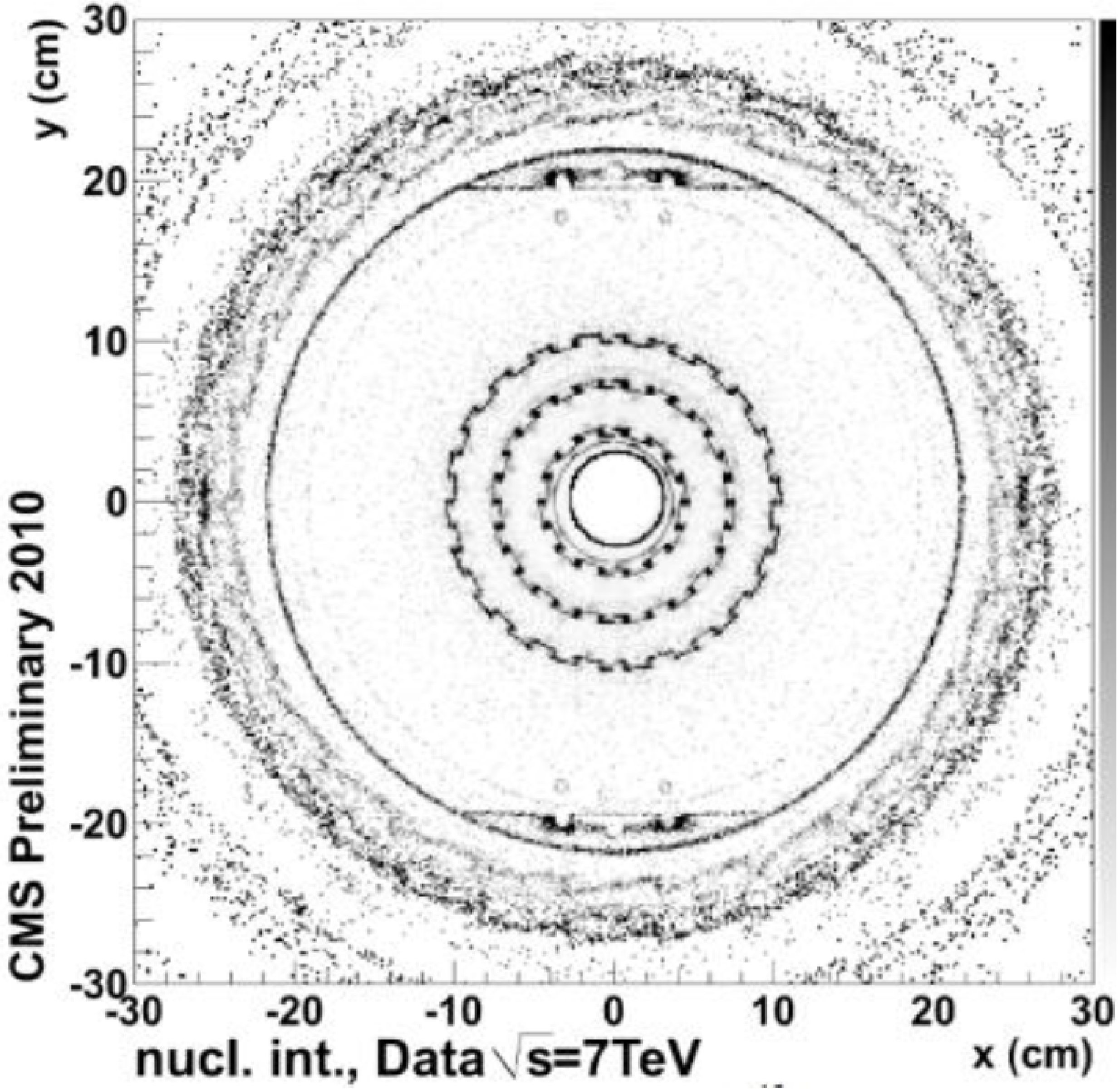
- Thin tubes, 50 bar
- material reduction

present 3 barrel pixel layers



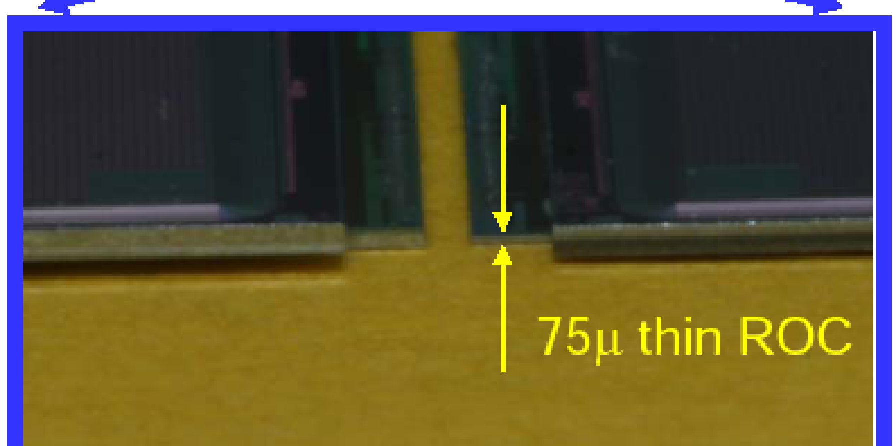
- Active length 52 cm.
- 3 layers:
  - <R> = 4.4, 7.3, 10.2 cm
- 768 modules
- 12'000 chips
- 51M pixels
- 1.5 kW
- 5.2 kg

Nuclear imaging



- Reconstructed nuclear interaction vertices.
- Barrel pixel region
- CMS tracker is shifted by ~3 mm relative to the LHC axis.

CMS pixel upgrade



Sensor 225µ thick

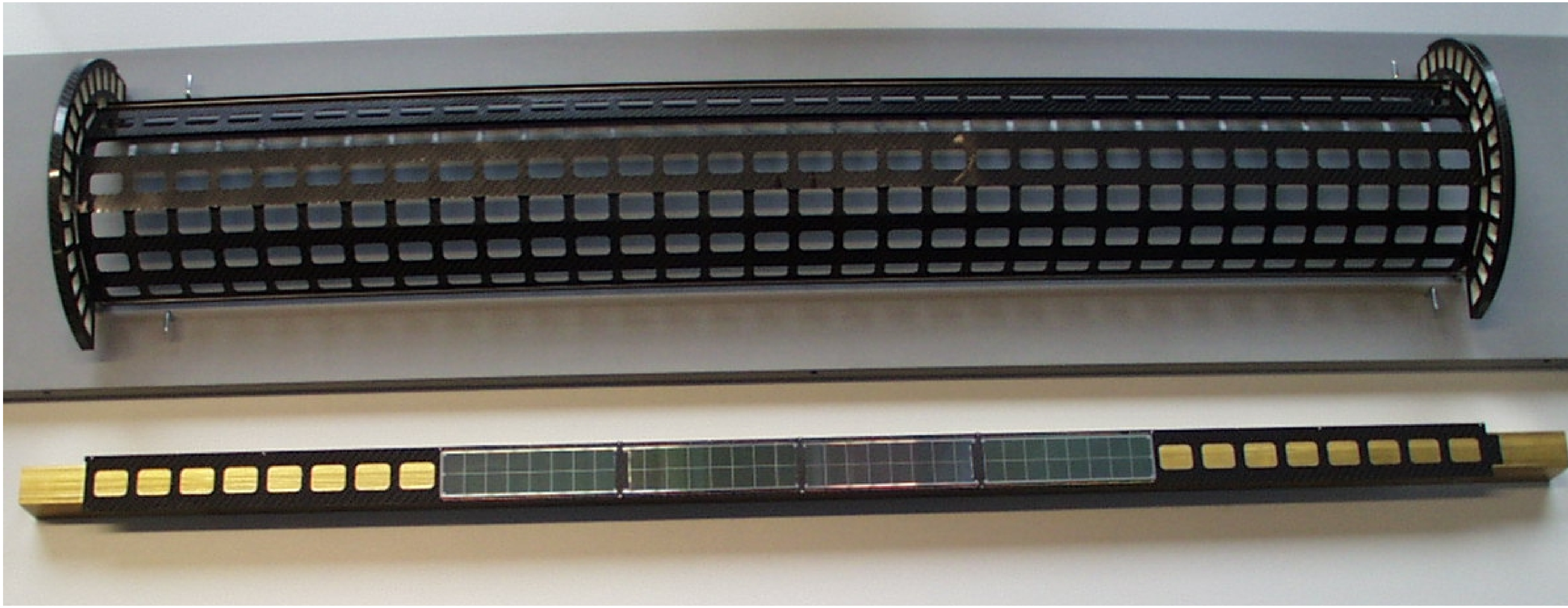
Future bare module

weight = 0.89 gr

→ 65% of present

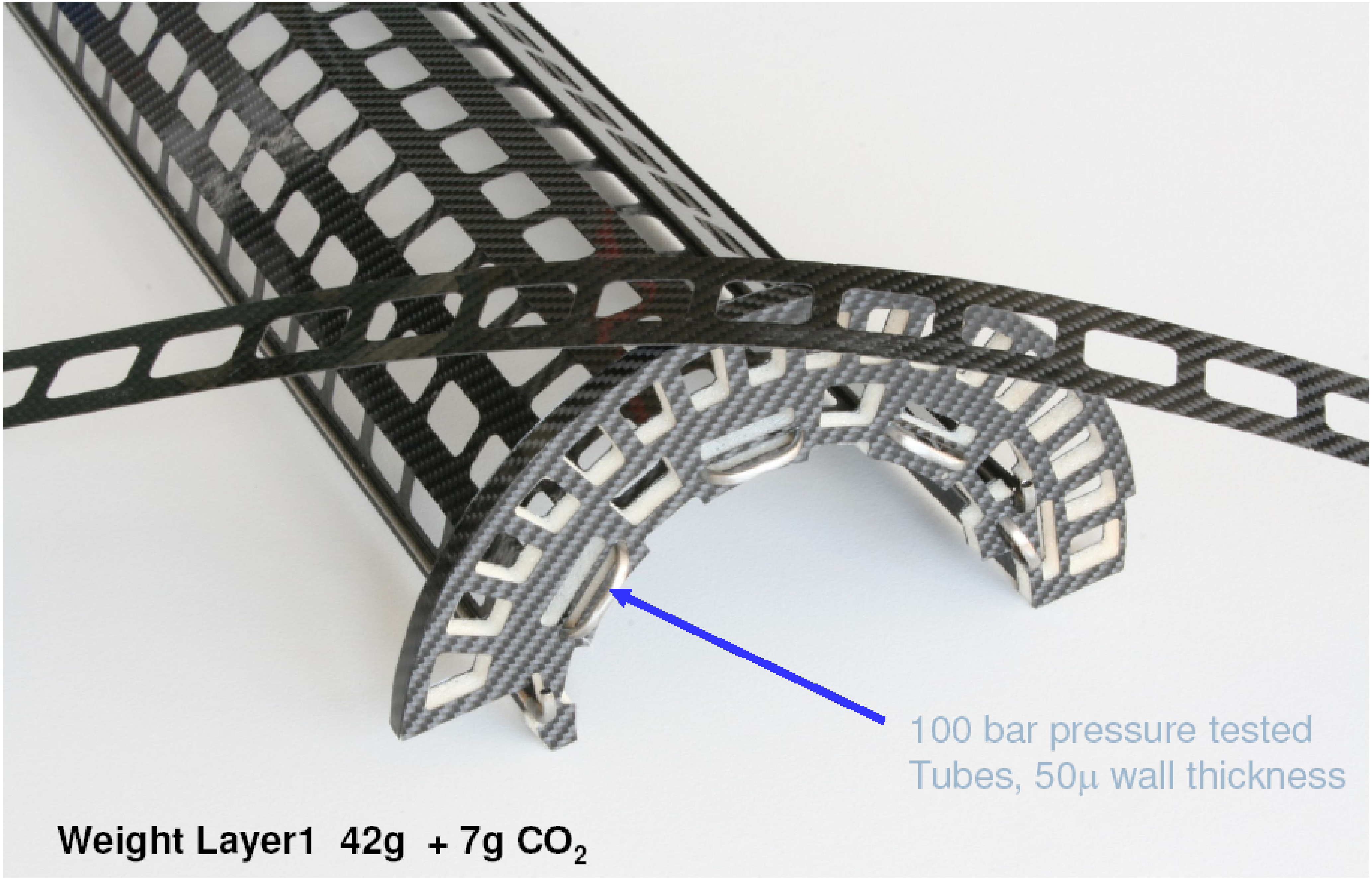
R. Horisberger
Jun '09

Upgrade carbon fiber frame

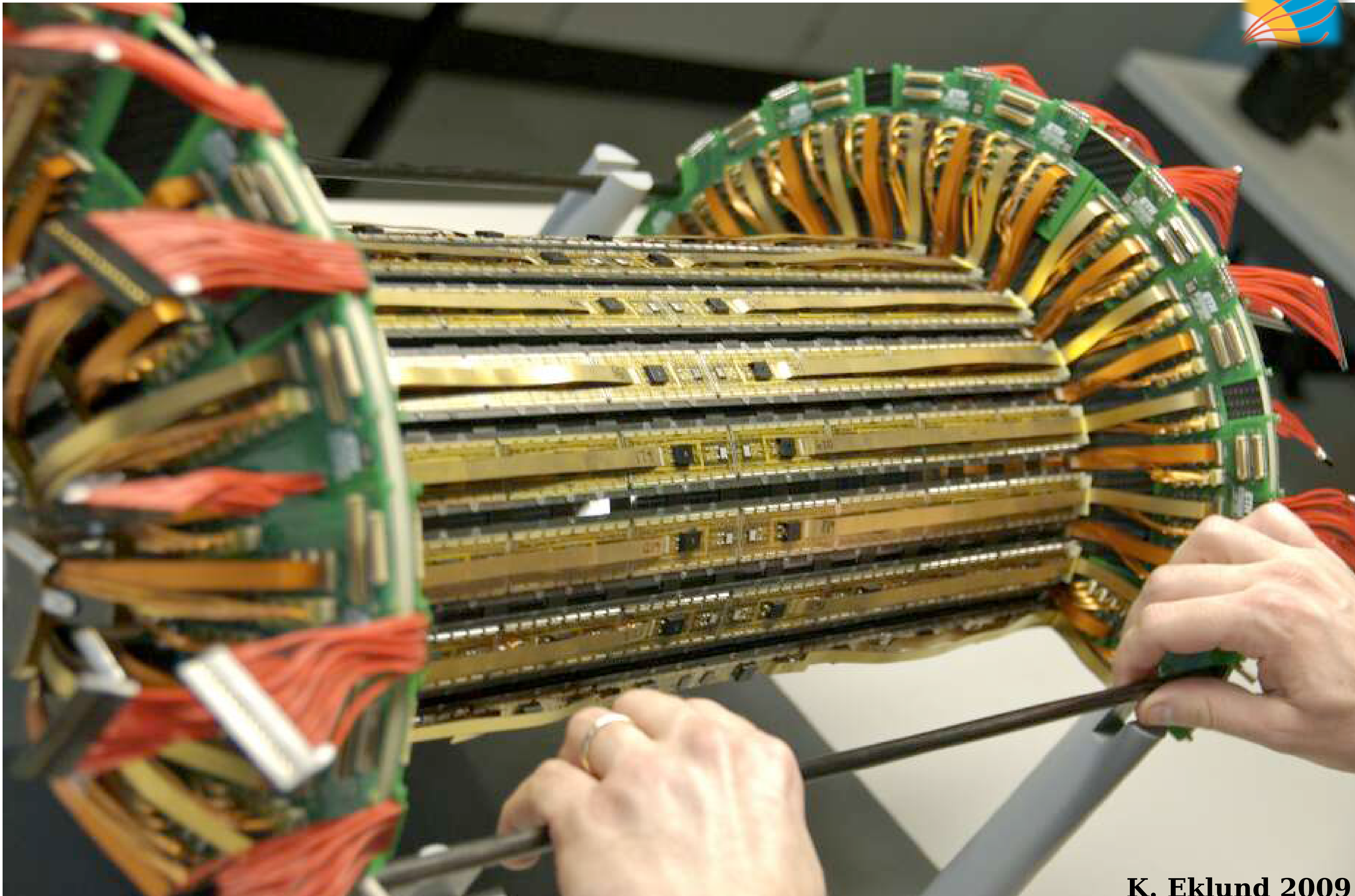


Ultra-leight weight carbon fibre frame and airex end flange with pipes for CO_2 cooling.

CMS pixel upgrade

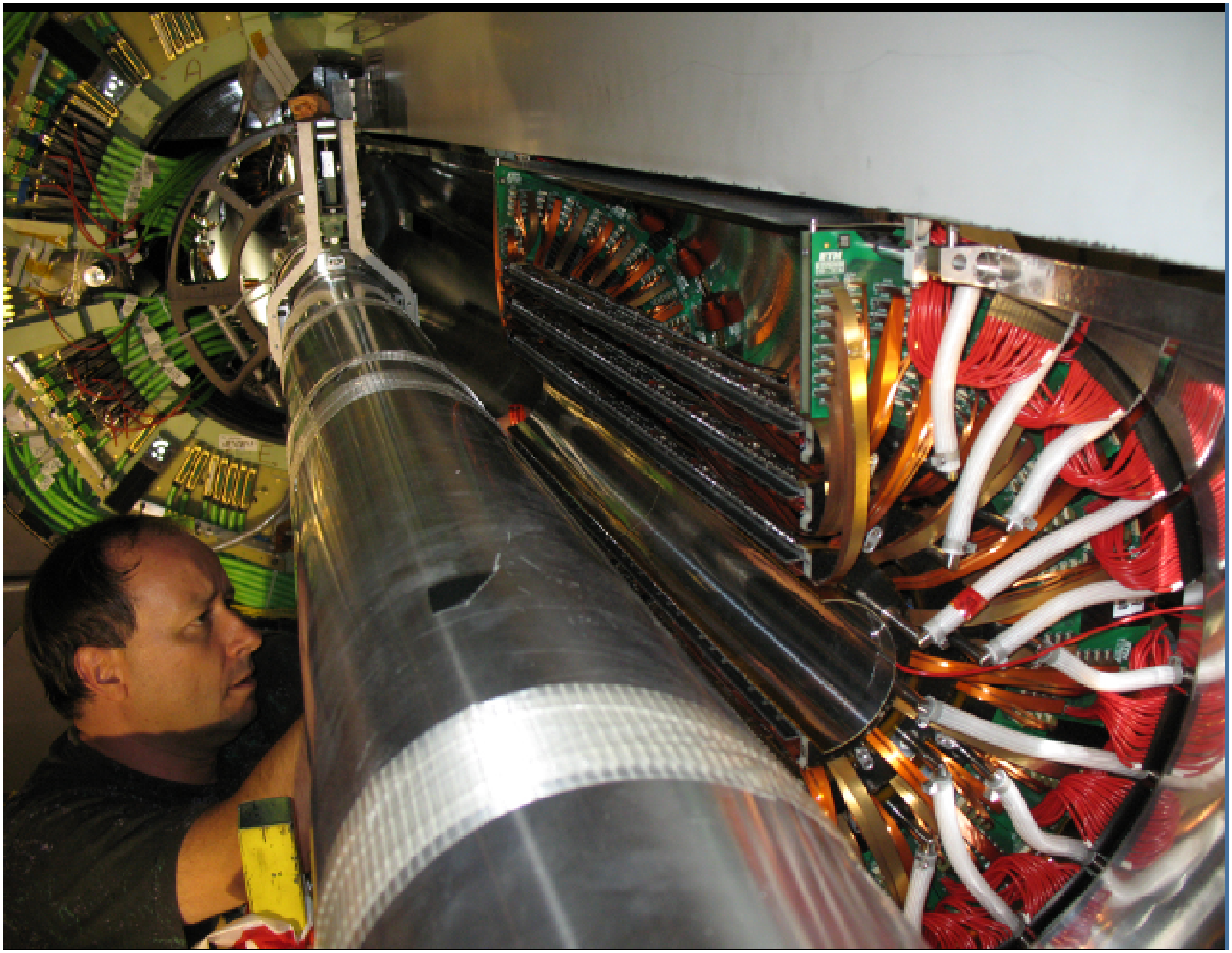


Present barrel pixel detector



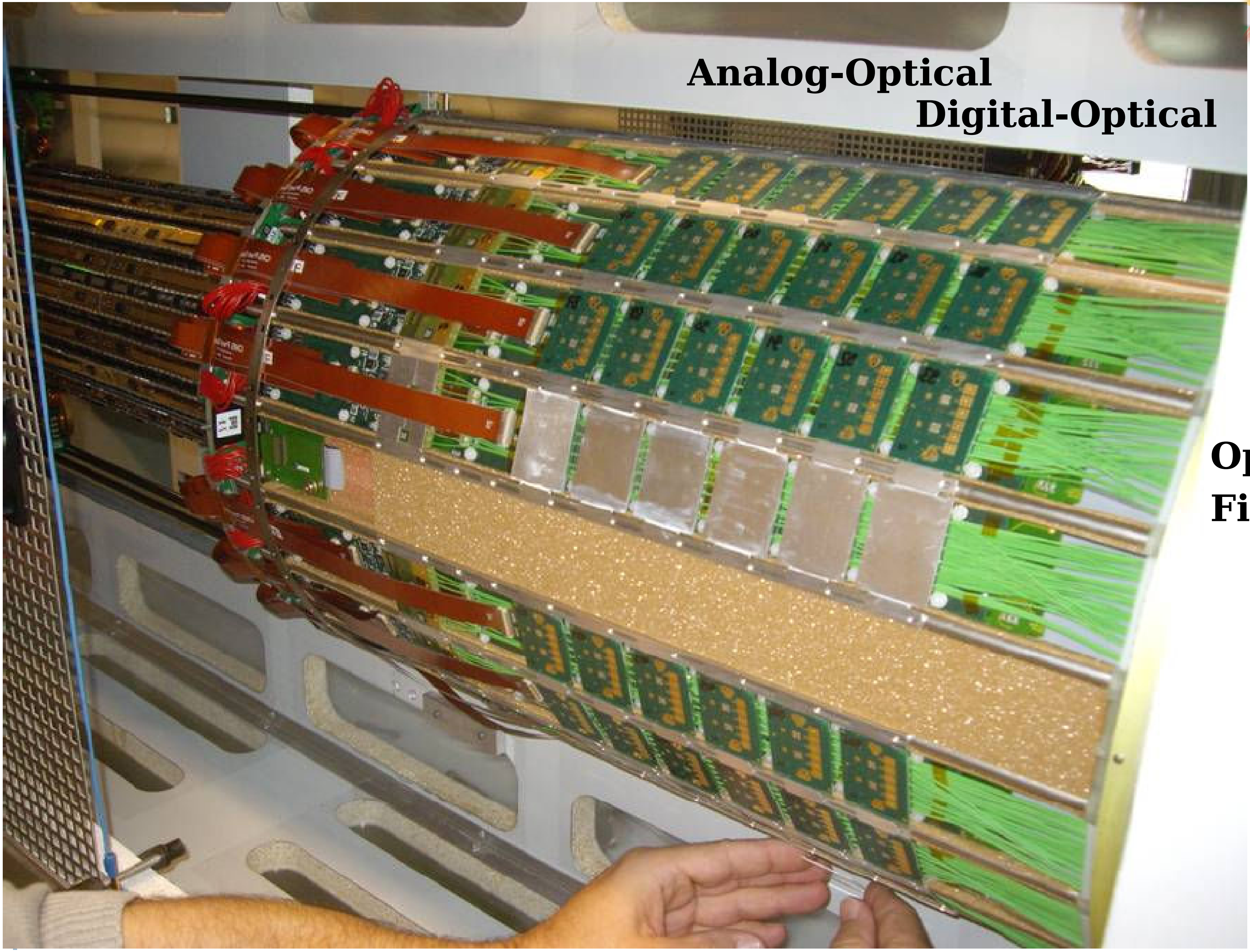
K. Eklund 2009

Barrel Pixel insertion 2008

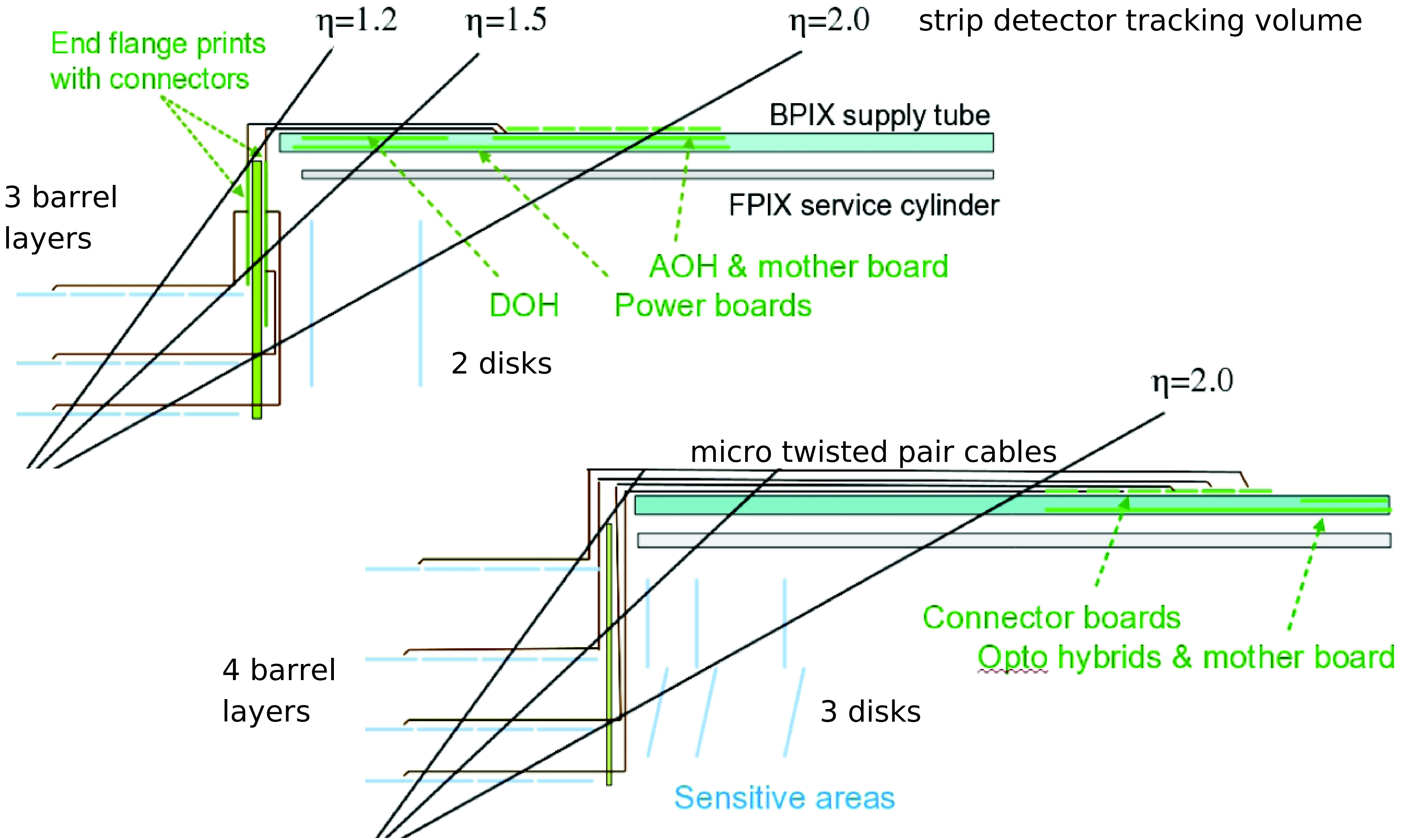


- The CMS pixel detector is accessible and removable during normal Christmas maintenance.
- Removal required for beam pipe bake out.

Barrel Pixel services

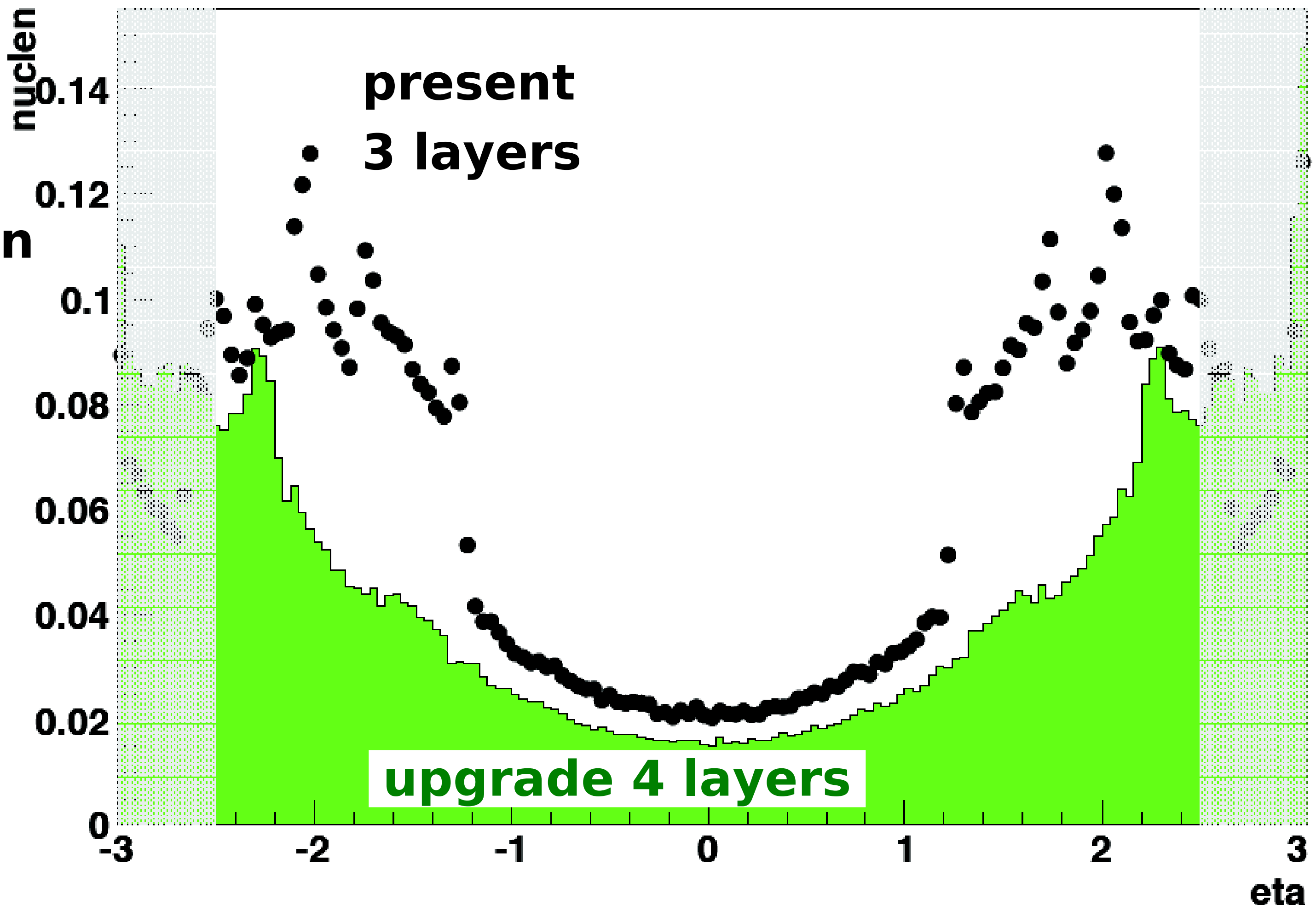


Moving readout material out of the tracking region



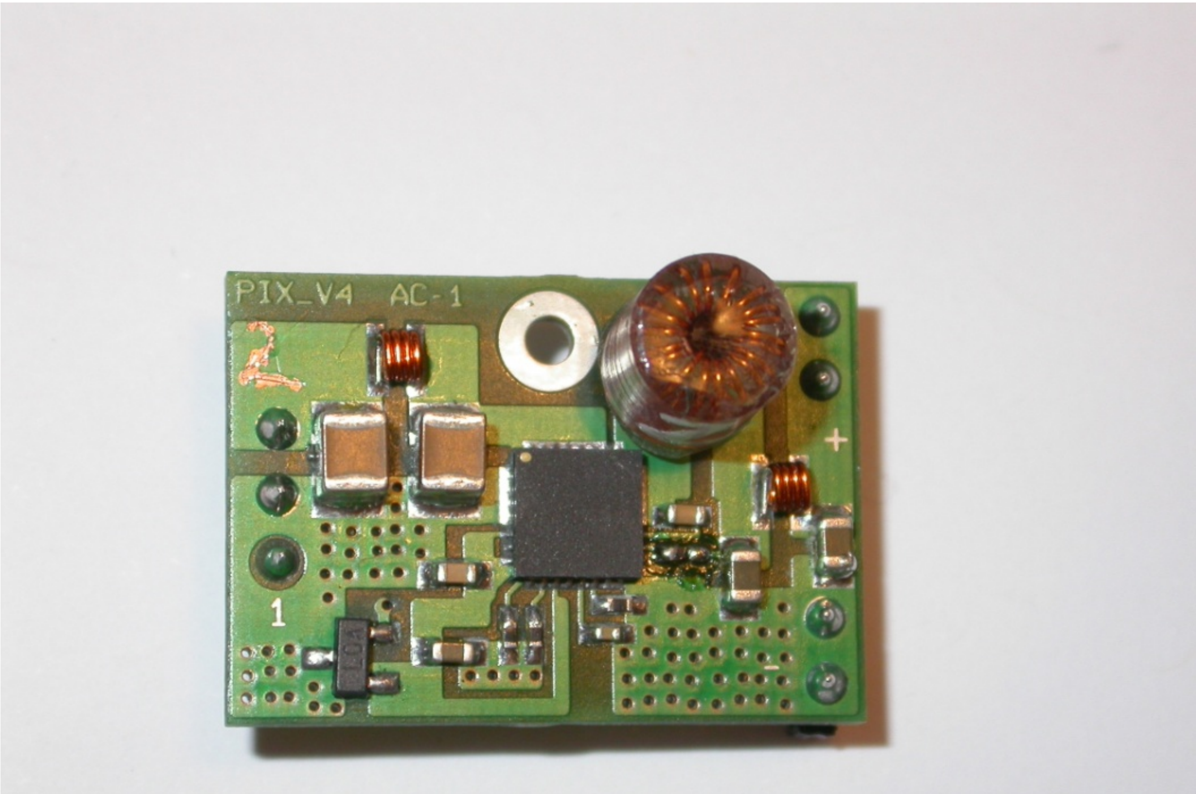
Barrel pixel material budget

nuclear interaction length



Up to 10% of all hadrons are lost due to nuclear interactions in the present CMS tracker.

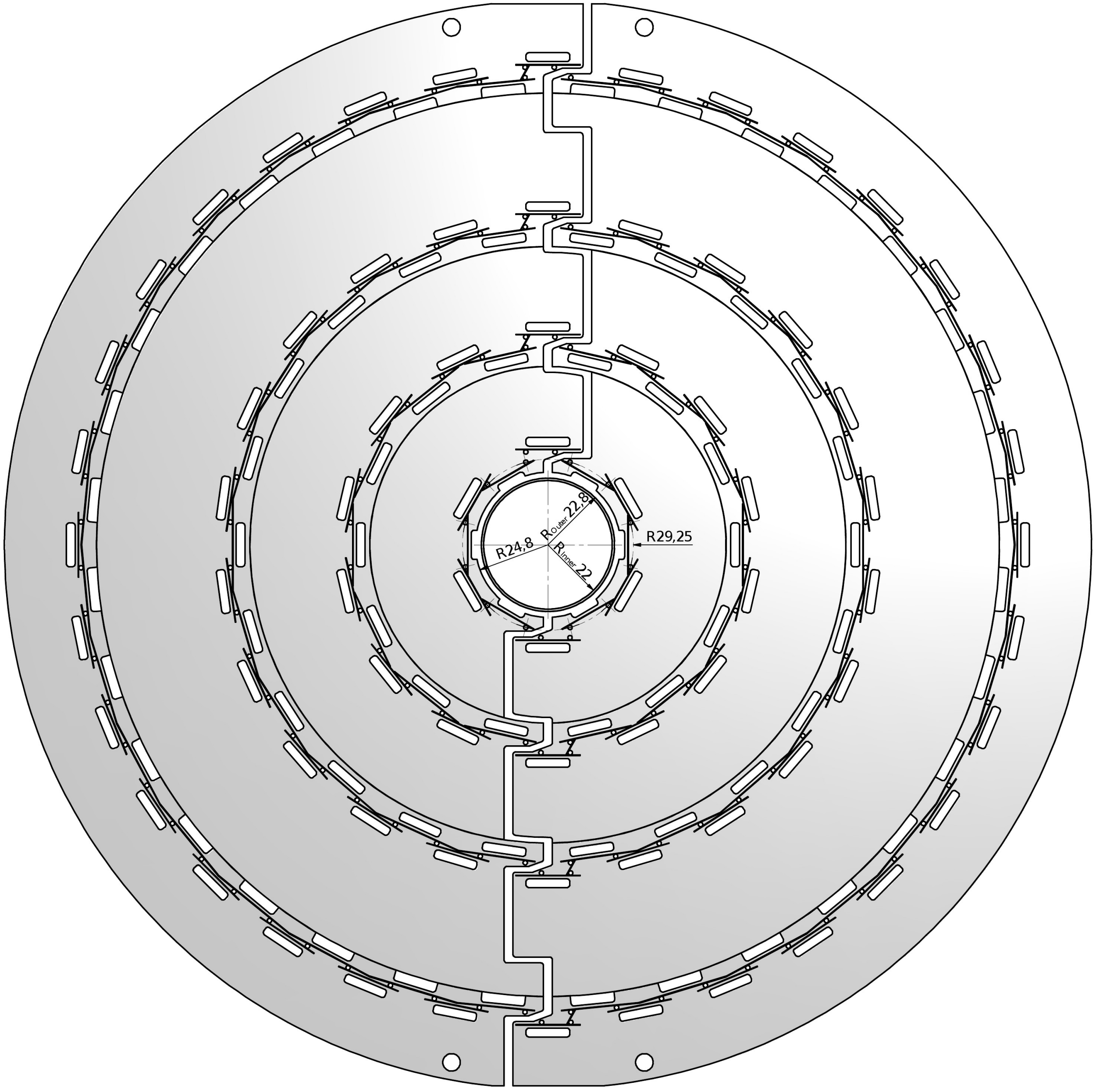
Services



- DC-DC converter developed in Aachen:
  - air-core coil, 10V → 3.3 V, 3 A, η=75%
  - radiation resistant AMIS 2 chip (CERN), switching at 1.2 MHz,
  - optimized design for low noise.

- CMS tracker cable channels are full:
  - have to use the existing services.
- Optical fibers:
  - go from 40 MHz analog to 320 MHz digital readout.
- Power:
  - Use DC-DC converters at the detector.
- Sensor bias:
  - 600 V → 1000 V.
- CO_2 cooling:
  - pipe-in-pipe for 100 bar.

CMS barrel pixel upgrade: 4 layers



2 identical half-shells.

1184 modules (79M pixels)

(1.6 × present barrel)

R_1 = 29 mm, 96 modules

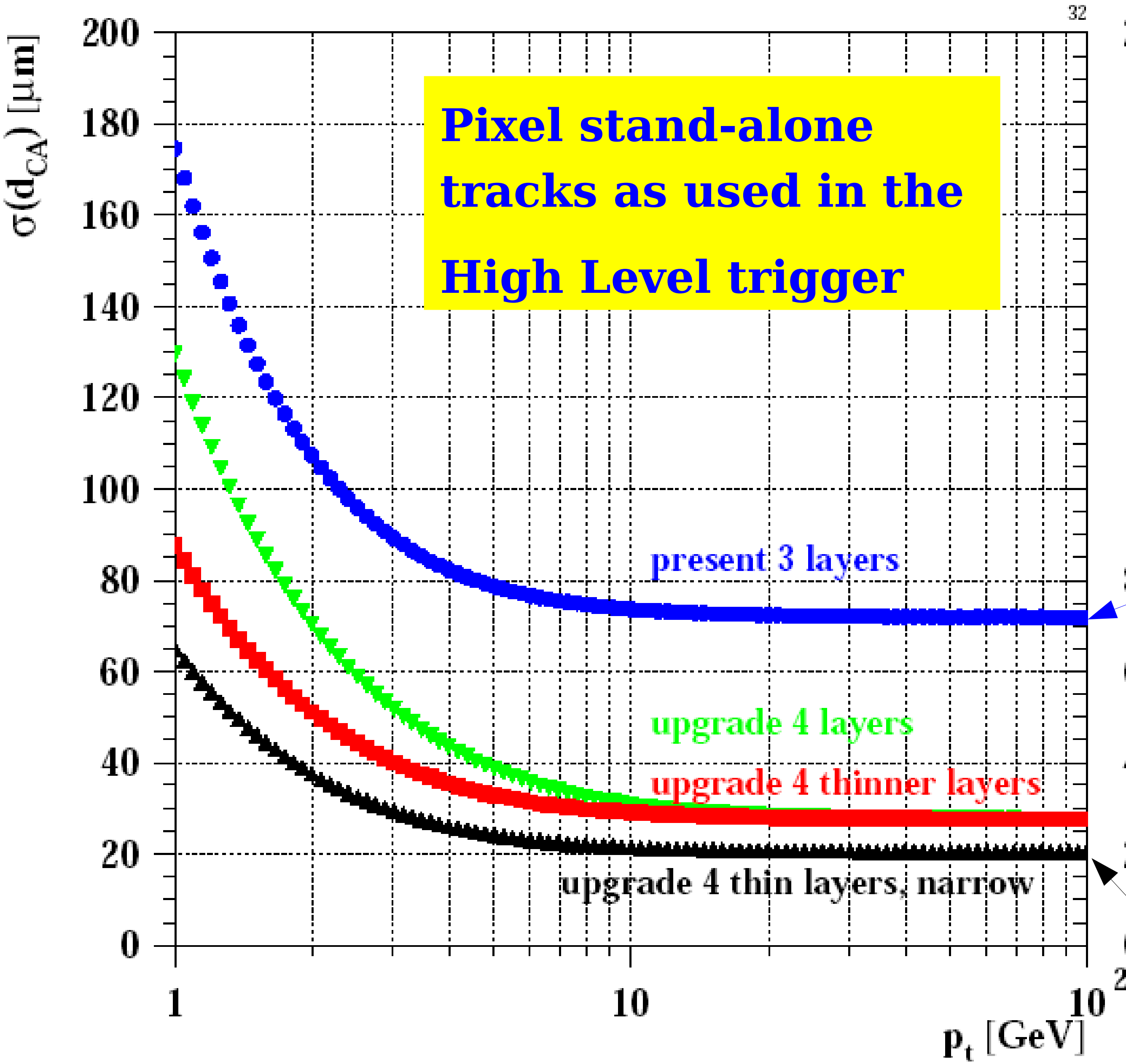
(R=22 mm beam pipe being negotiated with LHC machine)

R_2 = 68 mm, 224 modules

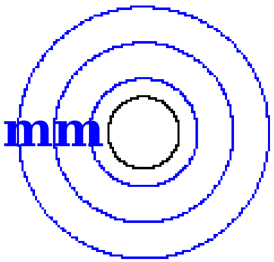
R_3 = 109 mm, 352 modules

R_4 = 160 mm, 512 modules

Pixel track impact parameter resolution

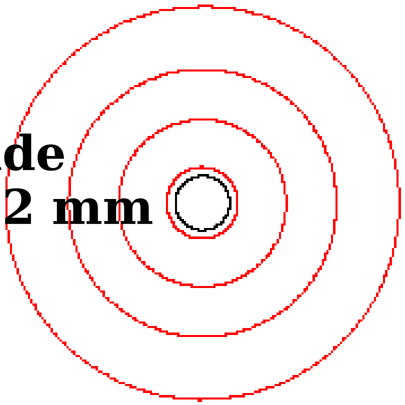


present
R_{BP}=29 mm



$\sigma(d_{CA})$ =
160 µm / pt ⊕ 72 µm

upgrade
R_{BP}=22 mm



$\sigma(d_{CA})$ =
62 µm / pt ⊕ 20 µm

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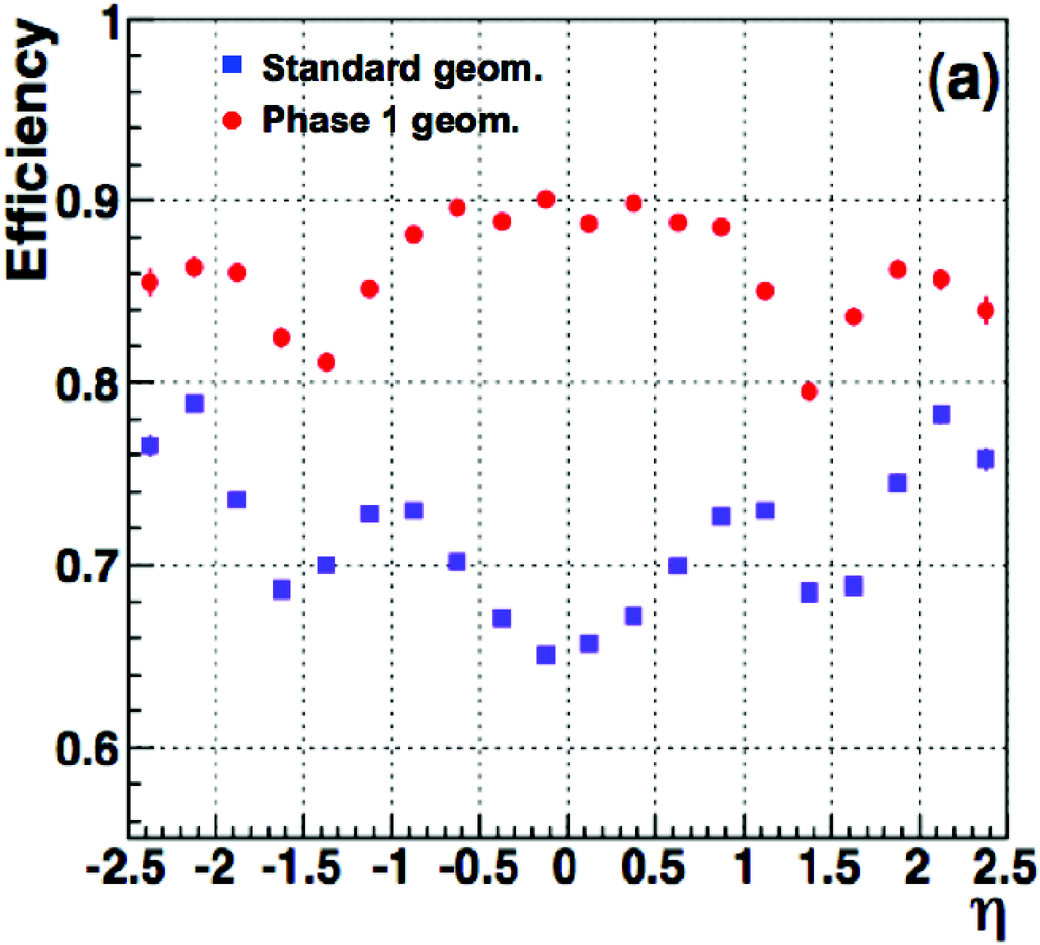
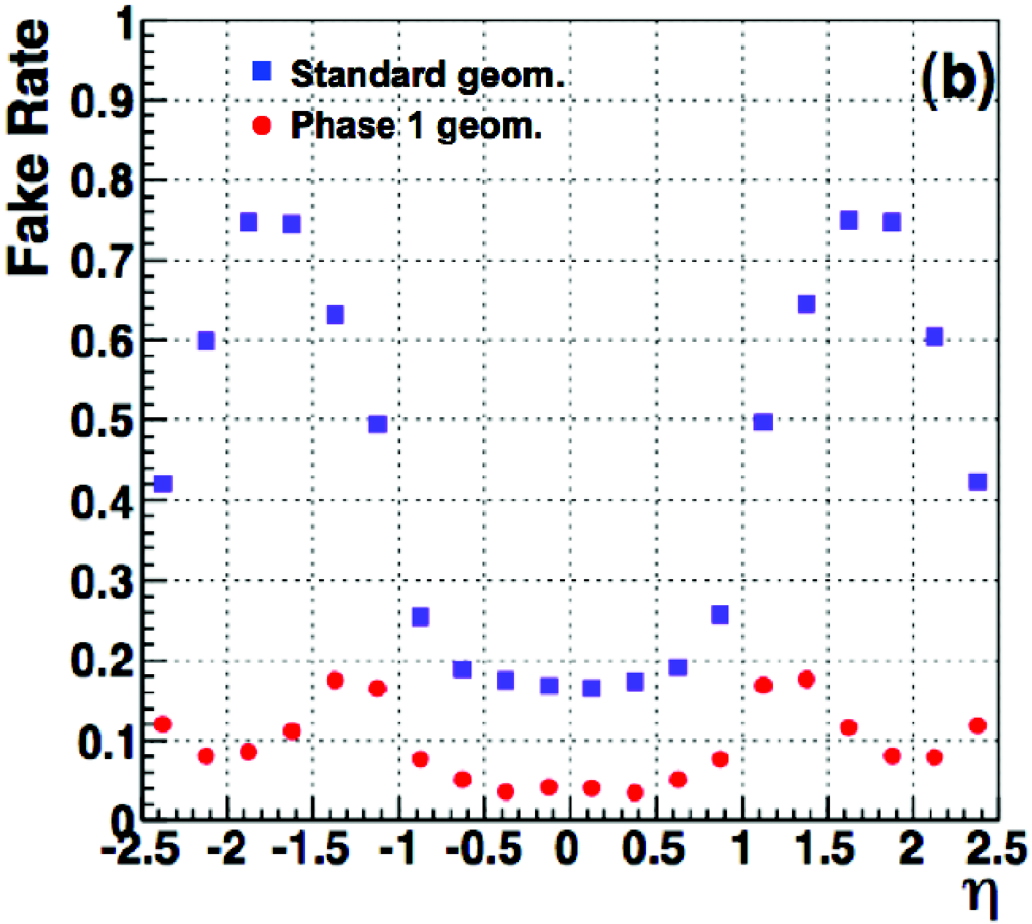
Tracking performance with pile-up 50

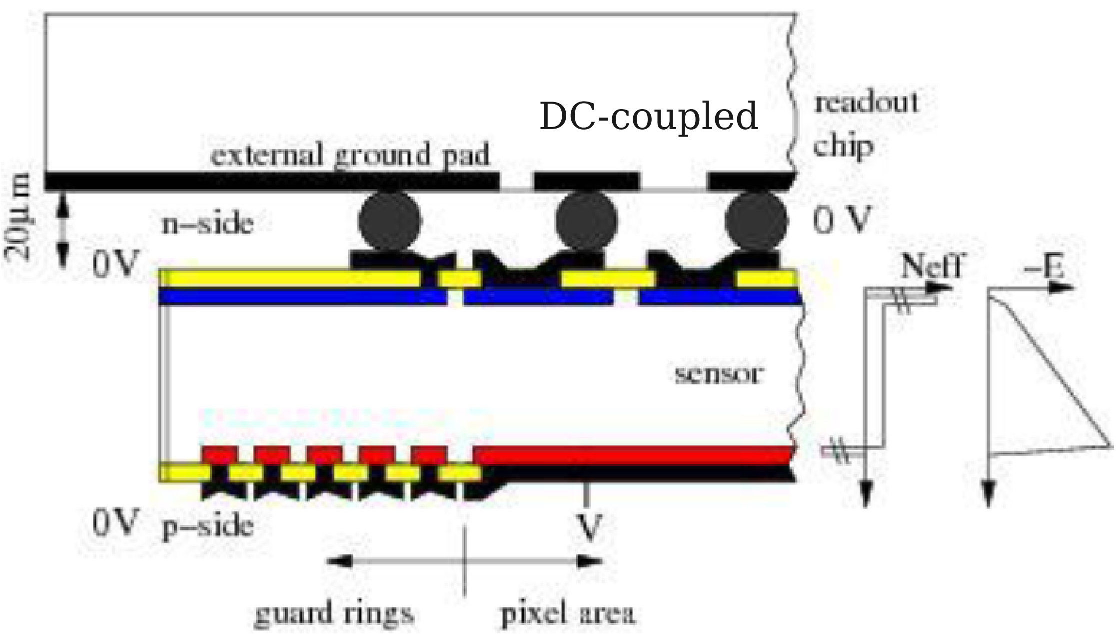
- t-tbar simulation with pile-up of 50 minimum bias events ($2\cdot10^{34}$ with 25 ns spacing).
- Pixel-based track seeding.



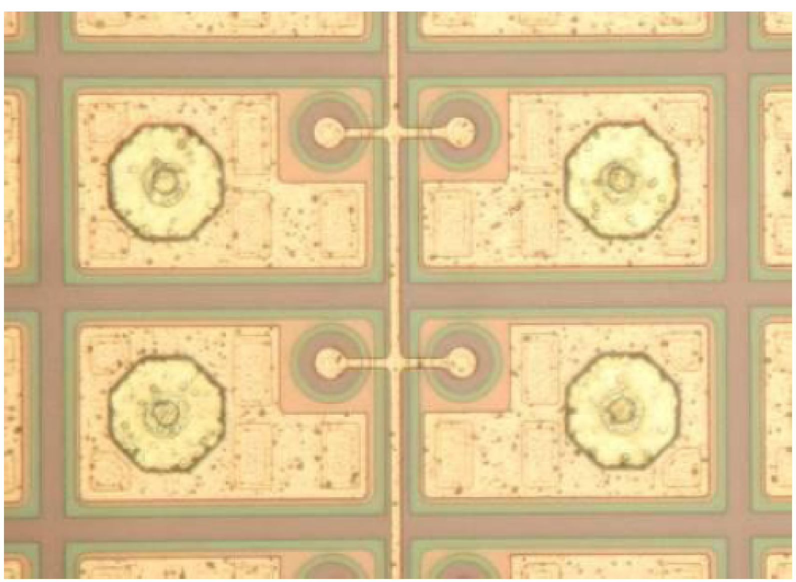


- **4-layer upgrade improves seeding efficiency**
- **4-layer upgrade reduces fake rate.**

Pixel sensors



- Planar sensors, CiS Erfurt.
- 111-oxygenated float zone.
- n-in-n, p-spray insulation.
- collecting faster electrons:
  - larger Lorentz angle,
  - less trapping.
- pn-junction on back side (initially):
  - edges at ground,
  - double sided processing.

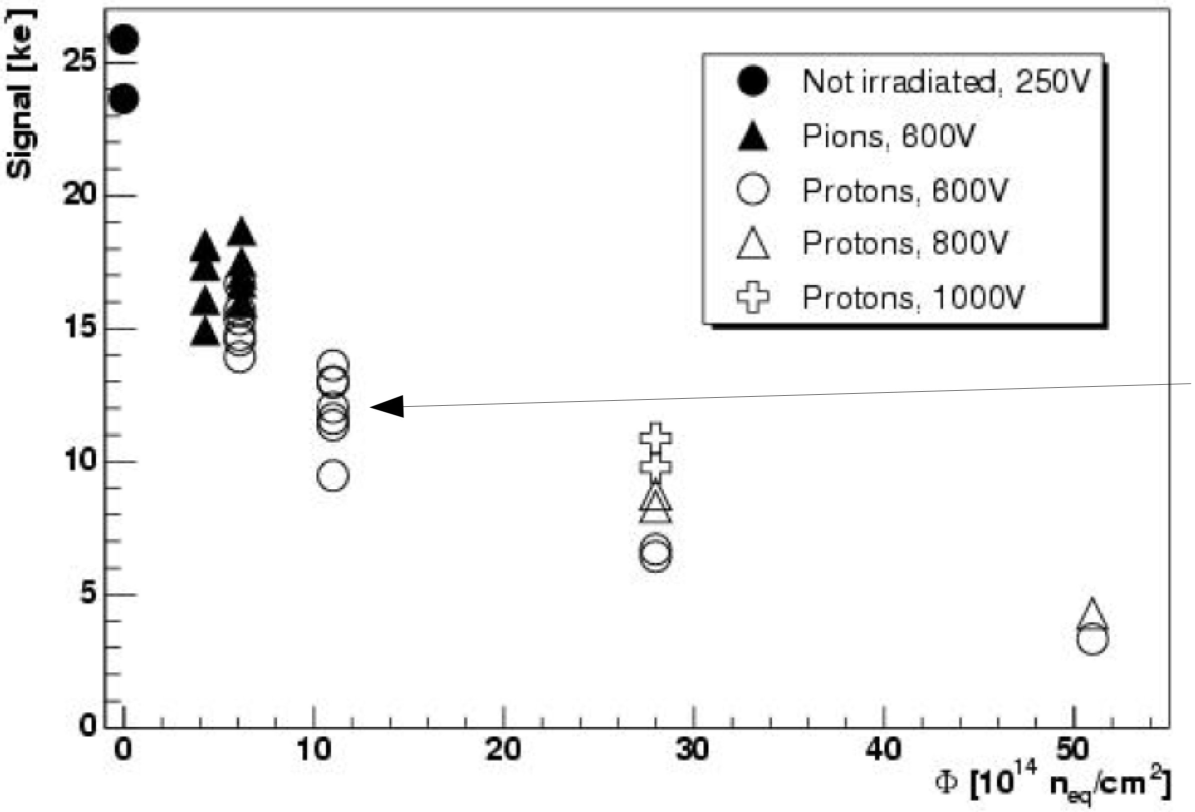


100 µm (rφ) x 150 µm (z).

Grounding grid for testing before bump bonding

Sensor radiation damage

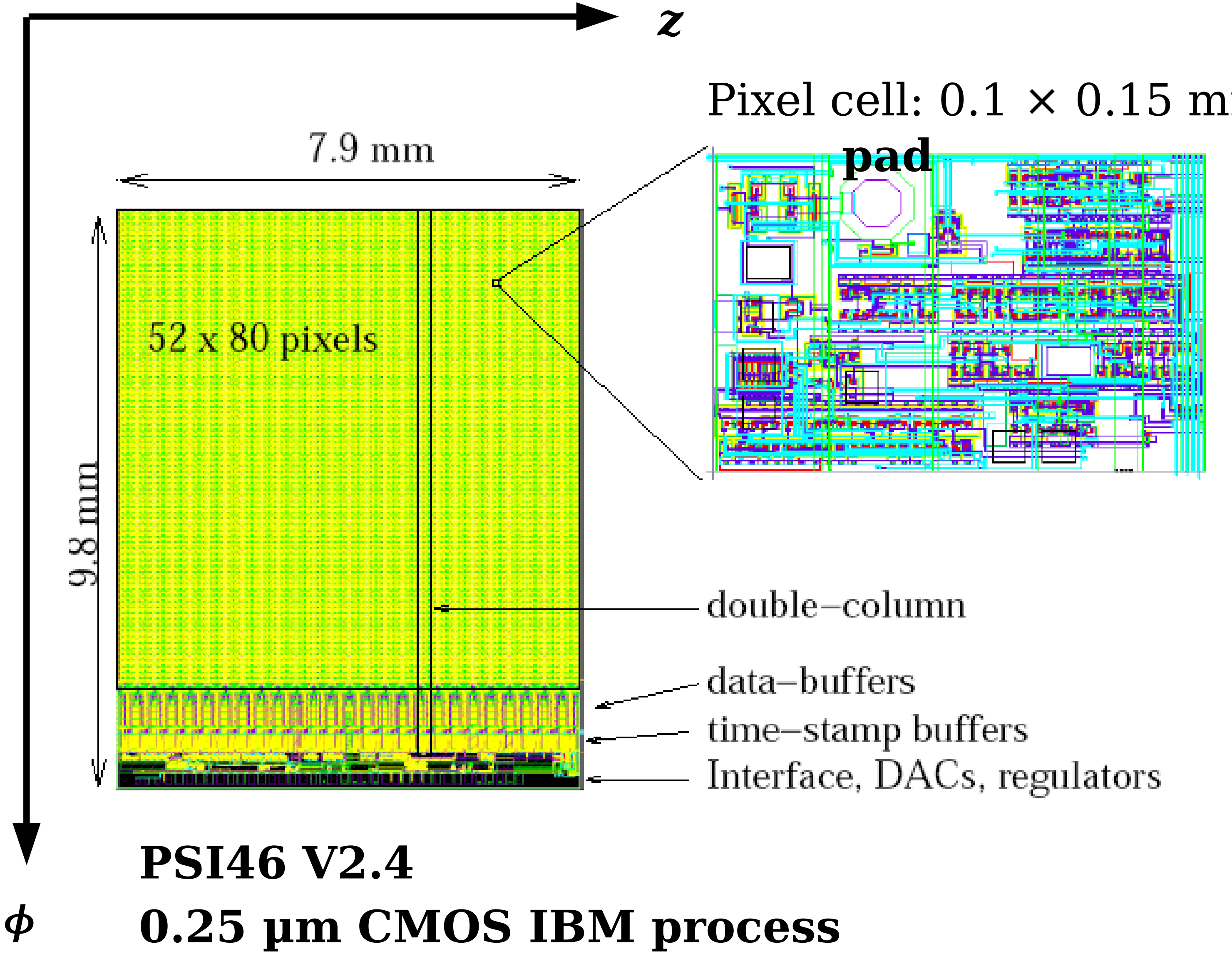
Signal collection in CMS pixel sensors



T. Rohe, Pixel2010

- Inner barrel layer:
  - 70 fb^{-1} = 4 · 10^{14} n/cm^2
  - 250 fb^{-1} = 13 · 10^{14} n/cm^2
- 50% signal loss after 250 fb-1.
- Also leads to factor 2 degradation of the hit resolution (less charge sharing and Lorentz angle
- Bias voltages above 600 V not possible with the present CMS HV system.
- MCz being considered.

CMS Pixel Chip



V_A = 1.5 V

V_D = 2.5 V

30 µW / pixel

0.12 W / chip

PSI46 V2.4

0.25 µm CMOS IBM process

radiation hard design operational after 130 kGy γ irradiation

1.3 M transistors

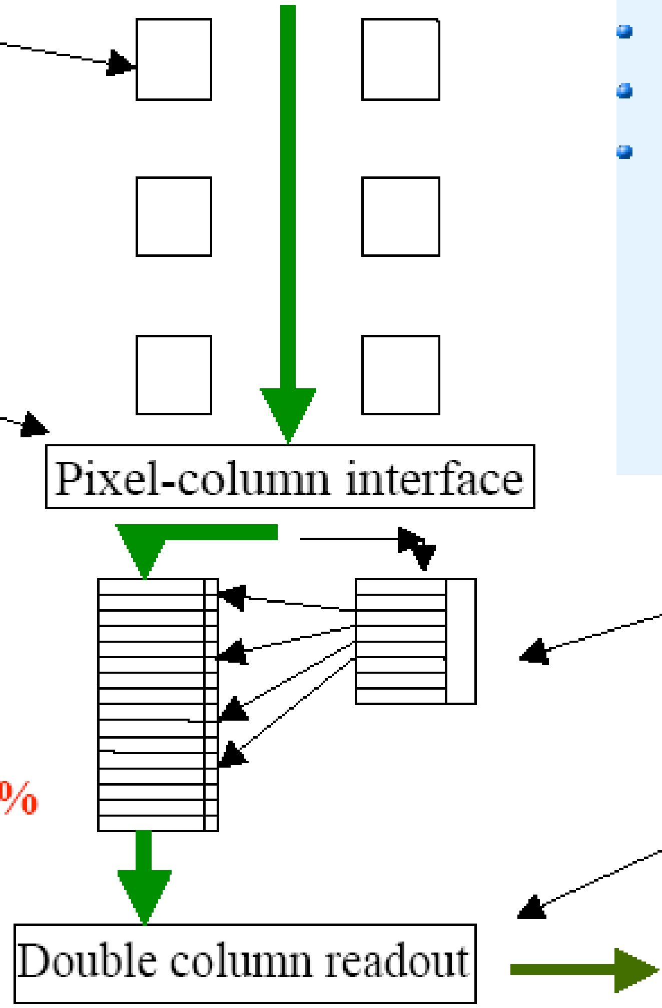
Data loss mechanisms

Present PSI46 readout chip simulated at LHC design luminosity

- 1xLHC: $10^{34} cm^{-2} s^{-1}$
- 11 cm / 7 cm / 4 cm layer
- total data loss @ 100kHz L1A:
  - 0.8%
  - 1.2%
  - 3.8%

Pixel busy:
0.04% / 0.08% / 0.21%
pixel insensitiv until hit transferred to data buffer (column drain mechanism)

Double column busy:
0.004% / 0.02% / 0.25%
Column drain transfers hits from pixel to data buffer. Maximum 3 pending column drains requests accepted



Timestamp Buffer full:
0 / 0.001% / 0.17%

Data Buffer full:
0.07% / 0.08% / 0.17%

Readout and double column reset:
0.7% / 1% / 3.0%
for 100kHz L1 trigger rate

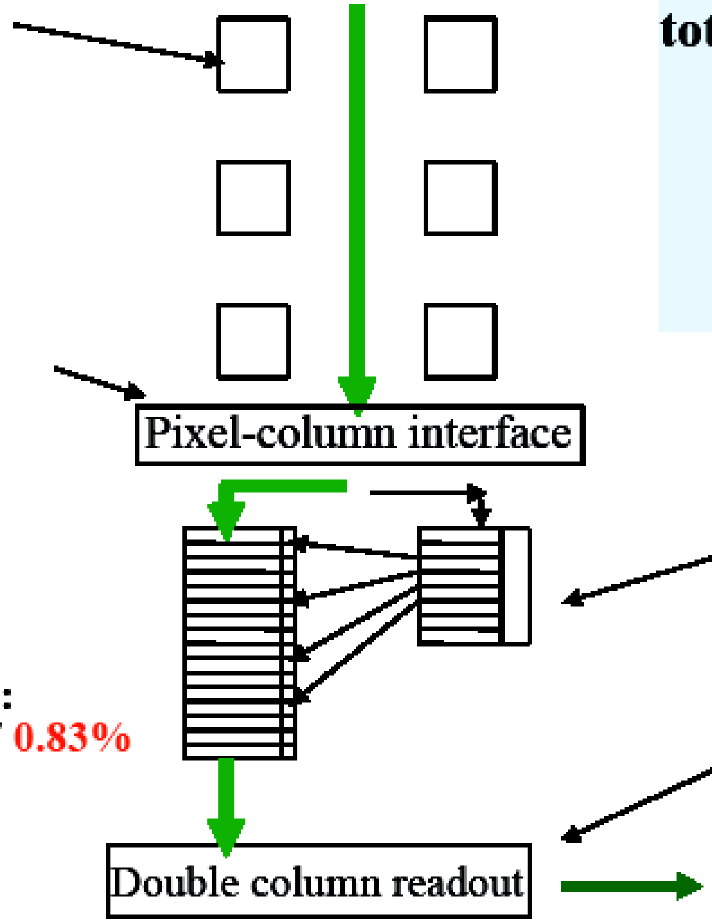
Data loss mechanisms

Present PSI46 readout chip simulated at 2× LHC design luminosity

Pixel busy:
0.09% / 0.18% / 0.48%

total data loss @ 100kHz L1A:
- 1.3% @ 11cm
- 2.7% @ 7cm
- 16% @ 4cm

Double column busy:
0.003% / 0.18% / 1.3%

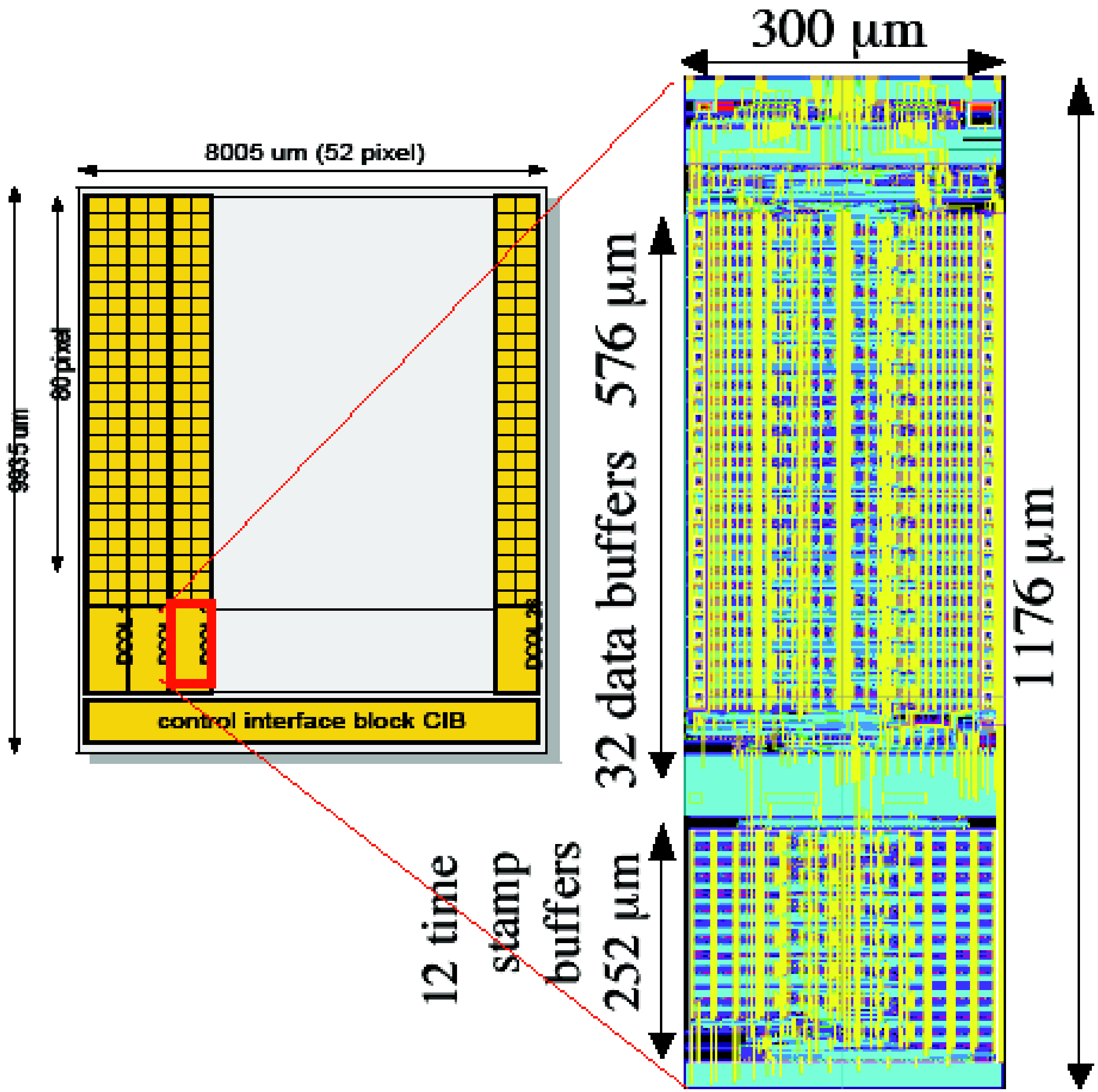


Timestamp Buffer full:
0 / 0.05% / 6.8%

Data Buffer full:
0.09% / 0.17% / 0.83%

Readout and double column reset:
1.1% / 2.1% / 6.7%
for 100kHz L1 trigger rate

Enlarged on-chip buffer



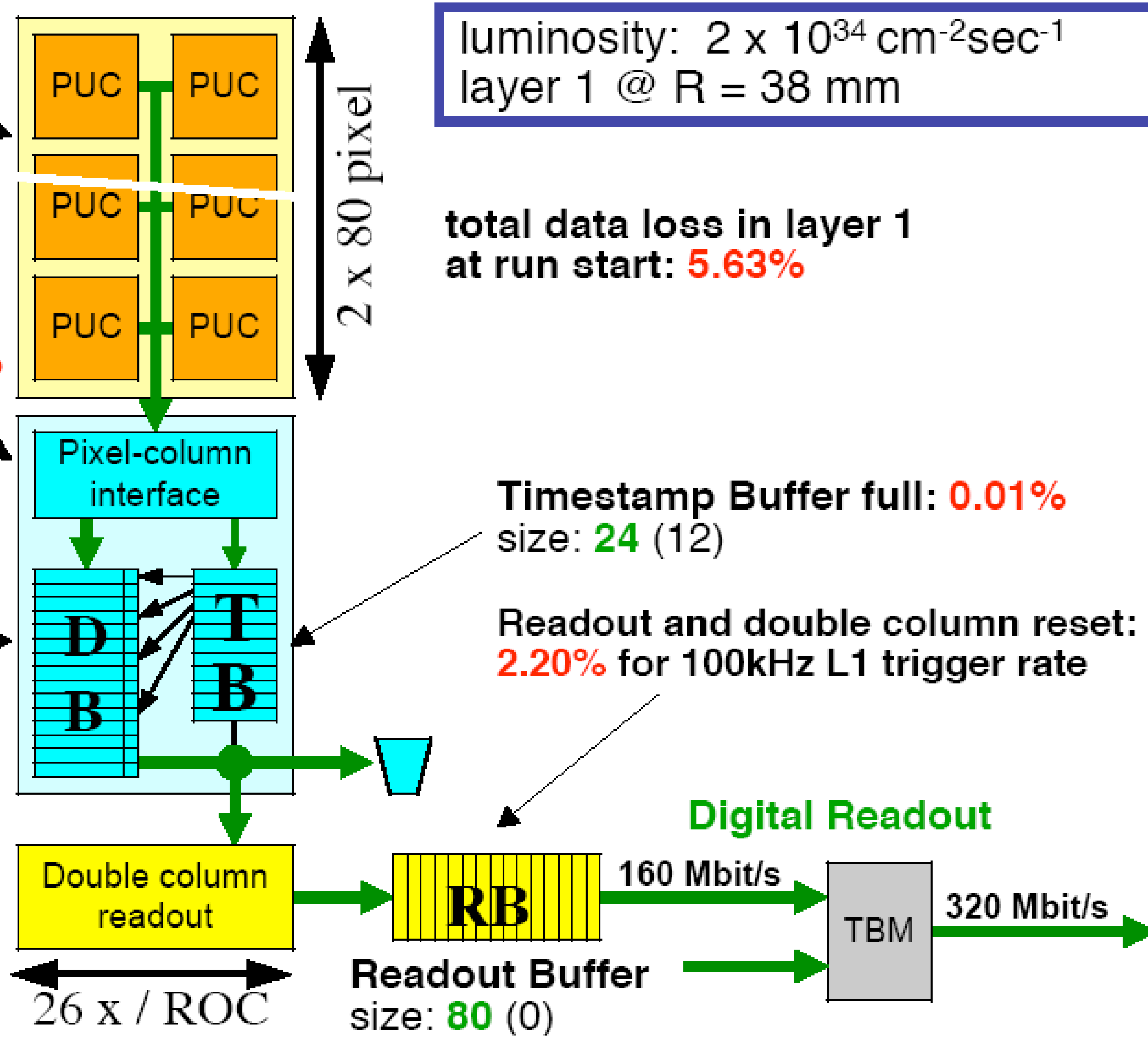
- **Dominant data loss mechanism → larger buffers needed**
- Data loss simulations performed
  - Data buffer from 32 to 80 cells
  - Timestamp buffer from12 to 24 cells
- Simple scaling would increase ROC size by >1.1mm
- 800 µm more space allowed with new detector mechanics
  - → Need more compact buffer layout

Data loss with extended buffering

Pixel busy: 0.72%
pixel insensitive until hit transferred to data buffer (column drain mechanism)

Double column busy: 2.03%
Column drain finds hitted pixels and transfers hits from pixel to data buffer. Maximum 3 pending column drains requests accepted

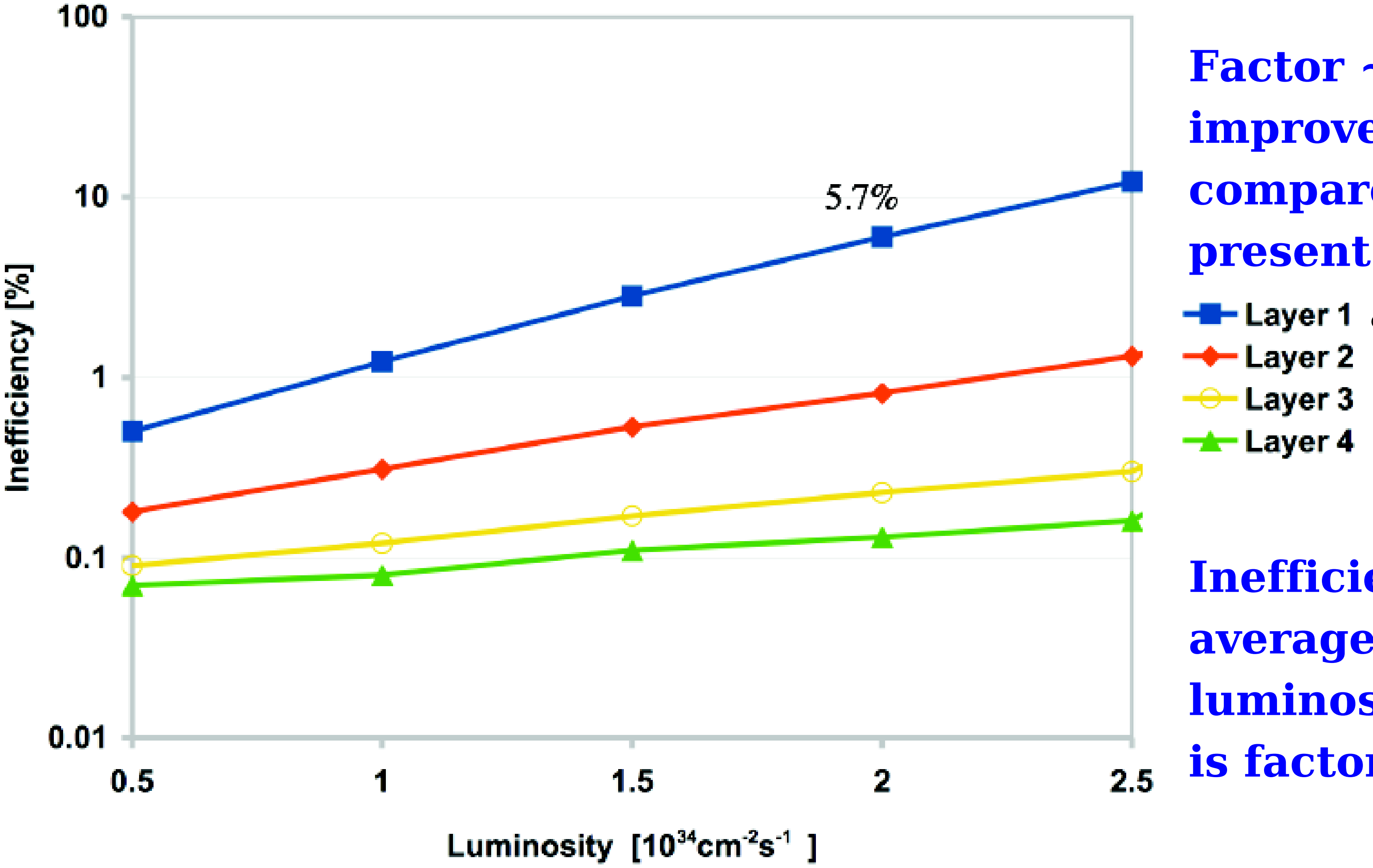
Data Buffer full: 0.68%
size: 80 (32)



H.C. Kaestli
Oct 2009

Data loss vs luminosity

Pixel readout chip simulation with increased buffering

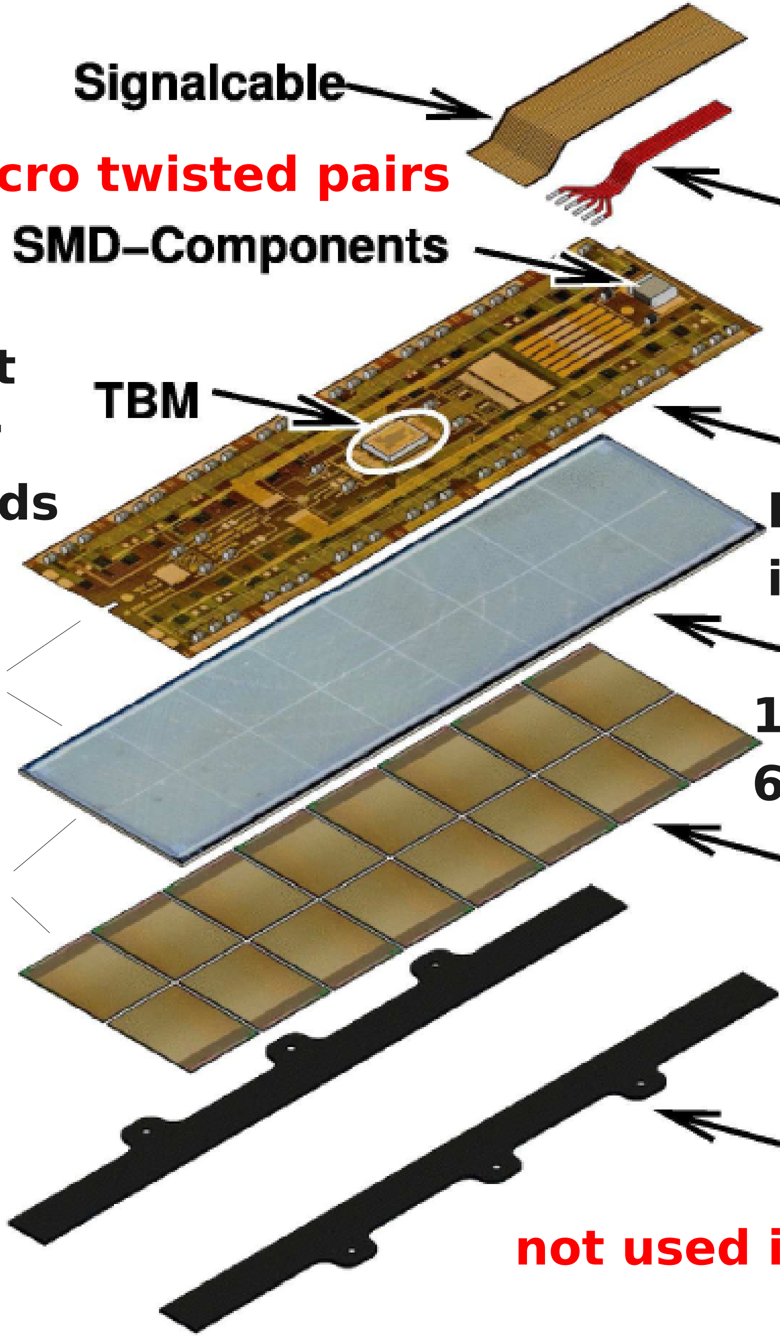


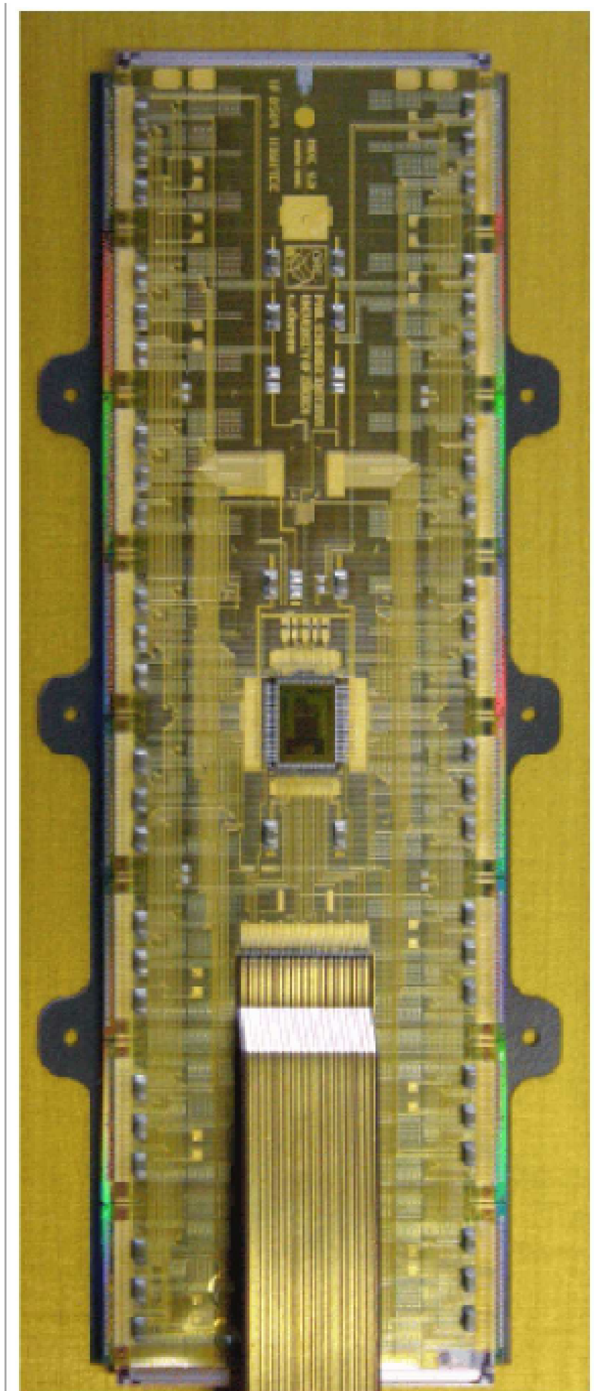
Factor ~3 improvement compared to the present chip.

Inefficiency averaged over a luminosity fill is factor 2 smaller

H.C. Kaestli
Oct 2009

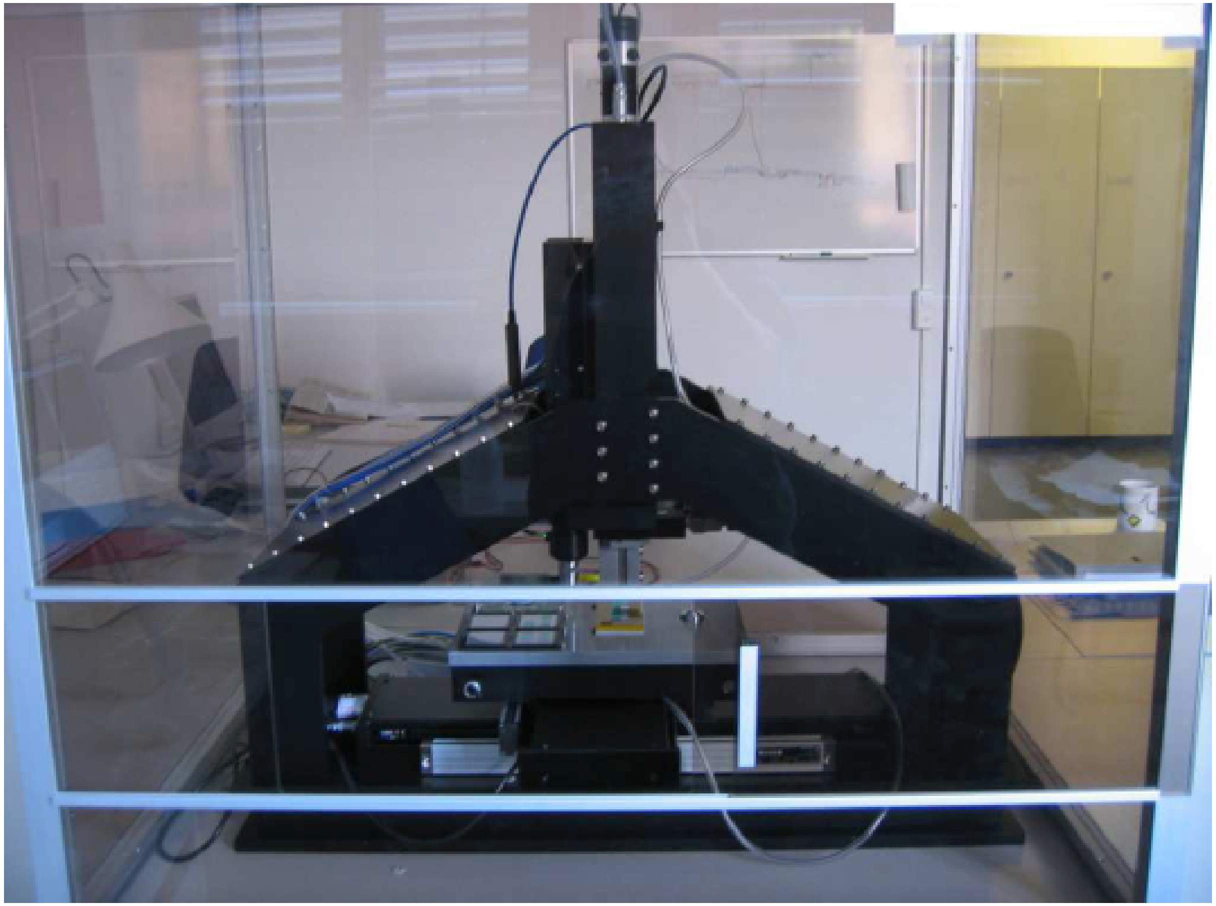
CMS barrel pixel module





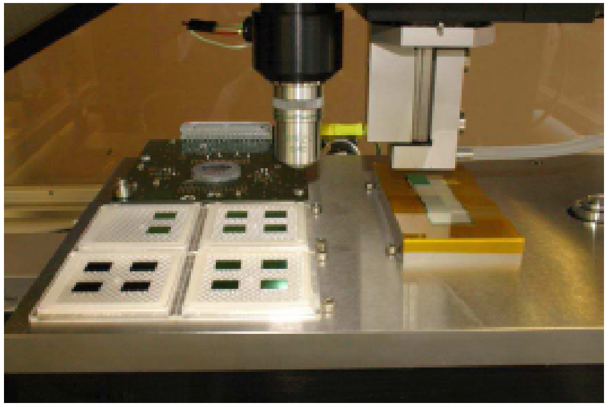
full–module ≙ 16 ROCs

CMS Pixel bump bonding



A. Starodumov

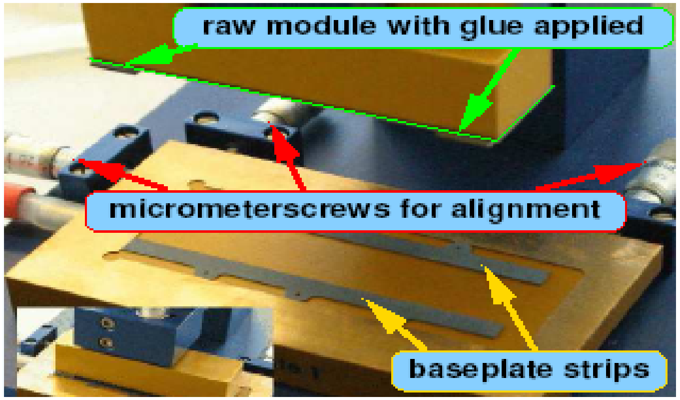
- Precision: $1 \div 2\,\mu m$
- Production rate:
  - 6 modules / day + tests
  - automated: 1 hr/module
- Bare module test:
  - IV-curve
  - ROC functionality
  - bump yield
  - rework: 80% success

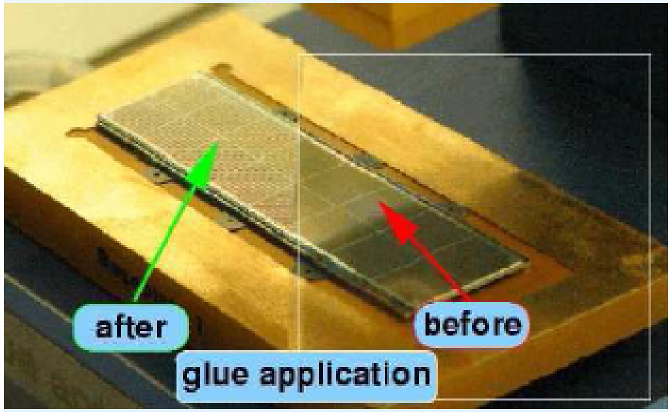


Precision *x-y-z* stage
Computer controlled
Commercially available.

CMS barrel pixel module assembly line

- Production rate:
  - 4 full + 2 half modules / day
  - or 6 full modules / day
- Three glueing steps:
  - glue basestrips to raw module
  - underfill sensor with glue
  - glue HDI to complete assembly
- Important: custom-made tools

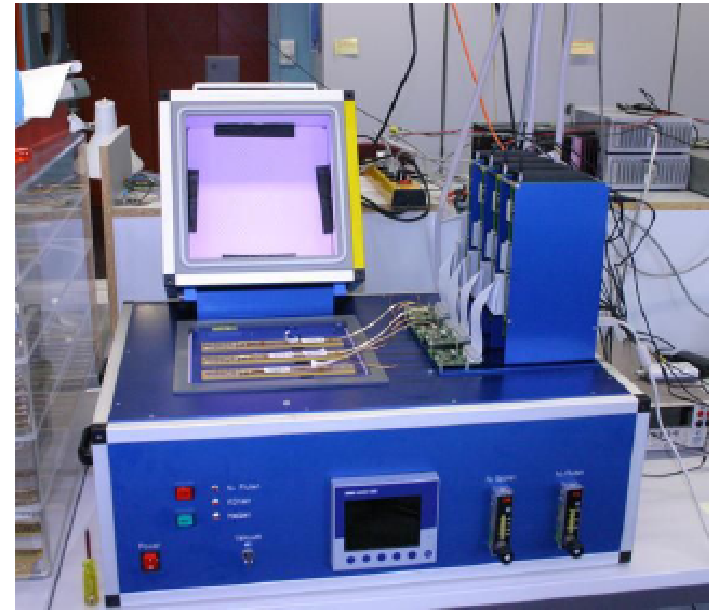


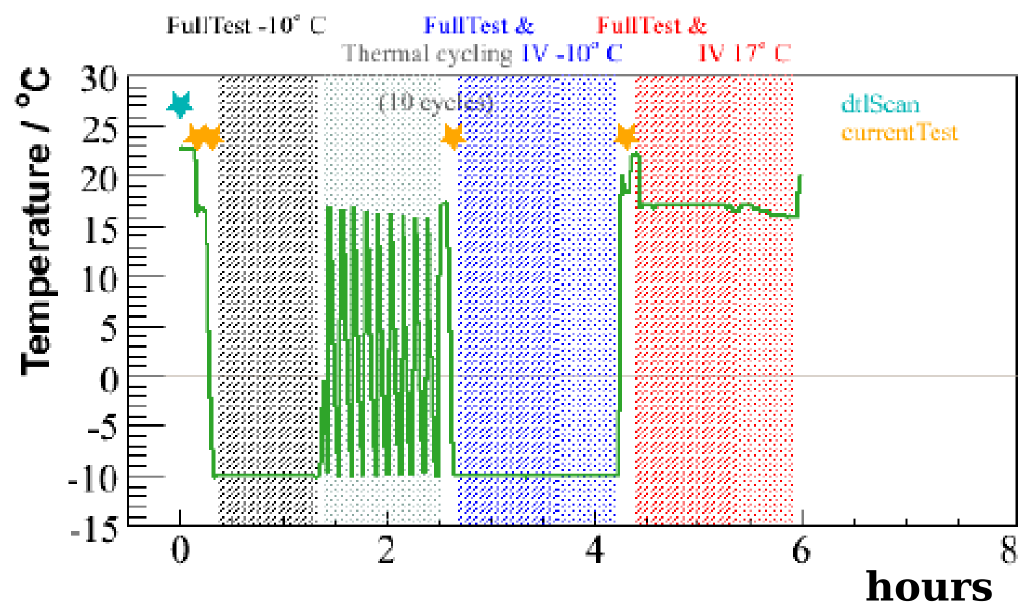


A. Starodumov

CMS pixel testing

- Challenges
  - Huge number of channels: $5 \div 6x10^7$
  - Multy-dimensional parameter space: 29 DACs/ROC
  - Temperature dependence: tests done at -10°C and +17°C
- Test set up
  - Programmable cooling box
  - 4 modules at a time
  - Castom built test-boards with FPGA
- Procedure
  - Start-up adjustments
  - Full Test at -10°C
  - 10 thermal cycles
  - Full Tests and IV at -10°C and +17°C





A. Starodumov

Work packages in D-CMS

4^{th} layer: 512 modules + 100 spares + 88 rejects = 700

task	quantity	DESY	HH	Ka	Ac
sensors I-V	700		350	350	
bare module test	700	350		350	
bond TBM to HDI	700	350		350	
glue HDI to sensor	700		350	350	
bond ROCs to HDI	400k	200k		200k	
module testing	700	350		350	
cold calibration	700	350			350
X-ray calibration	700		350		350
layer assembly	1	1			
layer system test	1	1			
DC-DC converters	many				all

Timeline

• Produce assembly tools	since 2010
• Develop assembly procedures	2011
• Develop testing and calibration procedures	2011
• Bump bonding tests	2010-2011
• Decide on bump bonding technique	end 2011
• Assembly and test procedures established	2012
• Receive all components for series production	2013
• Module assembly and calibration	2013-2015
• 4^{th} layer assembly and test	mid 2015
• Full system test at CERN	2015-2016
• Ready for installation in CMS	mid 2016

Summary

- The present CMS pixel detector is working very well and is an essential tool for track reconstruction and vertexing.
- The LHC luminosity is expected to exceed 10^{34} /cm^{2}s in this decade.
  - the present pixel readout chip will become inefficient.
  - at least the inner pixel layer has to be exchanged after 250 fb^{-1}.
- A 4-layer replacement with a new readout chip has further benefits:
  - Better resolution, efficiency, and purity for pixel-based tracking,
  - Reduced material in the tracker volume with CO2 cooling, low mass design, and repositioned converters.
- The German CMS institutes have been asked to contribute:
  - Design optimization and physics evaluation,
  - module assembly and testing,
  - DC-DC converter development and production.
- Preparations are underway.

PSI pixel test board at DESY