The Phase 1 upgrade of the CMS pixel detector

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On behalf of the CMS Collaboration

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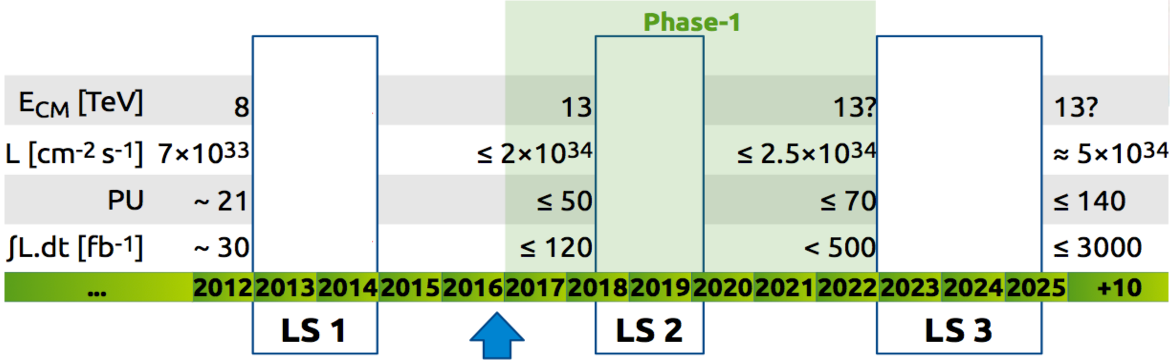
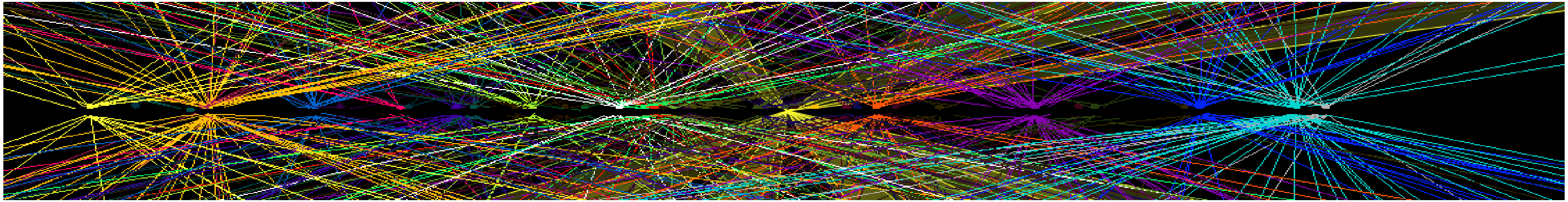
Motivation for the upgrade

- Pixel detector – performance currently is excellent
  - Used in seeding tracks, determining primary and secondary vertices

- High pile-up data at the LHC
  - Present detector was designed to operate at 10^{34} $cm^{-2}s^{-1}$ @ 25 ns bunch spacing
  - LHC expects to reach 2.5 times that intensity and 70 PU before LS3



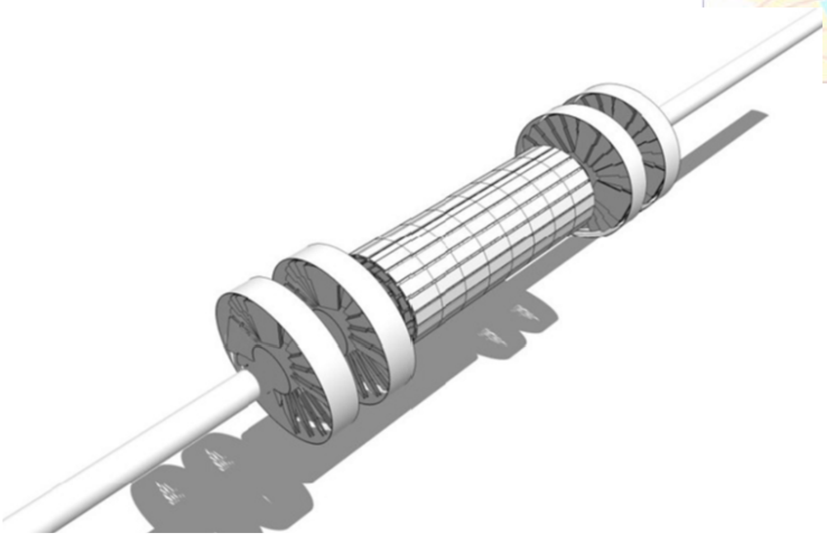
- Use for a new detector
  - Larger occupancy challenge for front-end electronics
  - Higher track multiplicity requires more efficient seeding
  - Higher number of PU requires better vertex separation



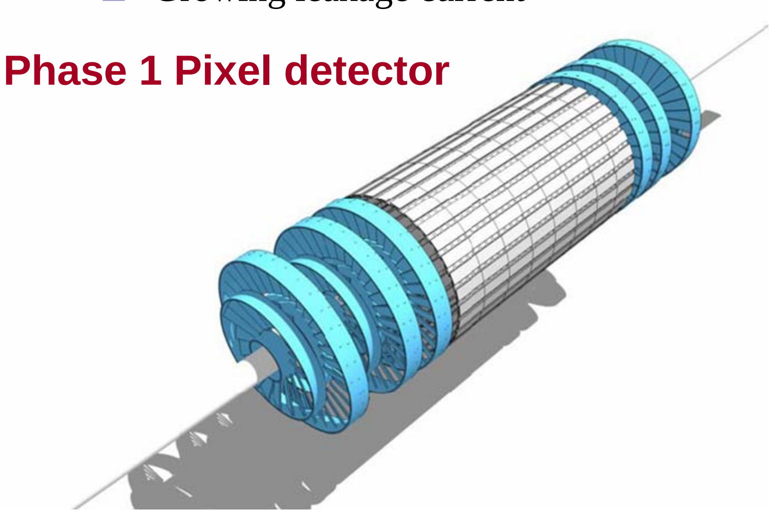
Motivation for the upgrade

- Another factor is aging: present detector was designed to perform up to ~100 fb^{-1} – a few 100fb^{-1} expected until LS3
- Radiation effects
  - Trade-off between full depletion and LA induced charge-sharing *(although slightly overdepleeting the detector this year gave us a one-off improvement in resolution)*
  - Delpetion voltage would eventually reach power supply limit
  - Growing leakage current

Current Pixel detector



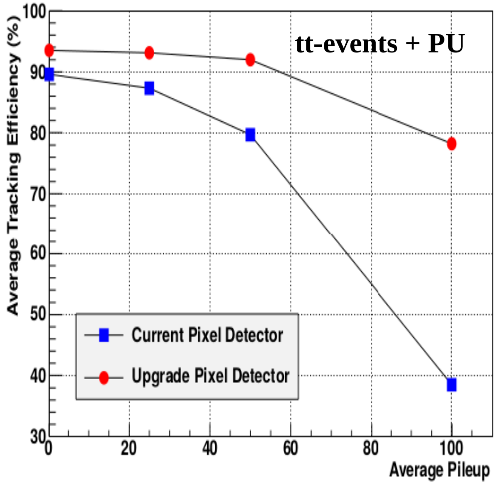
Phase 1 Pixel detector

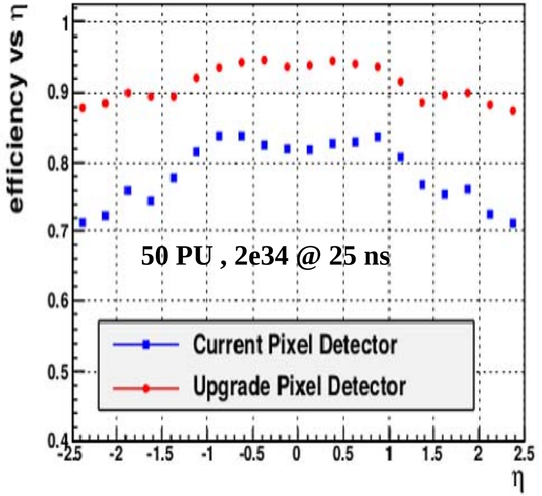


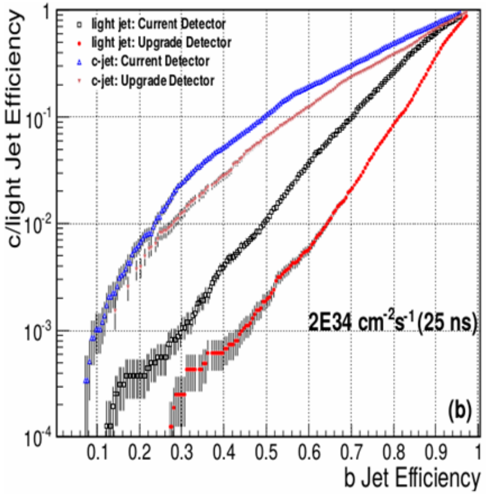
- Goal is to maintain or improve present performance
  - New detector improves on the shortcomings of old one
  - But keeps the original design wherever possible
- Physics reach – higher energy results in boosted jets provided dense environment, less track-separation

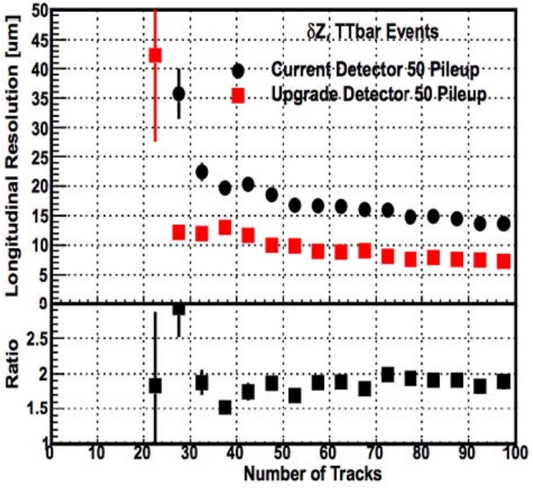
Expected physics performance

- Preliminary performance estimates based on MC simulation
- Eliminates strong dependence of tracking efficiency on event PU
- Better coverage in higher pseudo-rapidity; advantage since forward measurements gained importance in physics searches



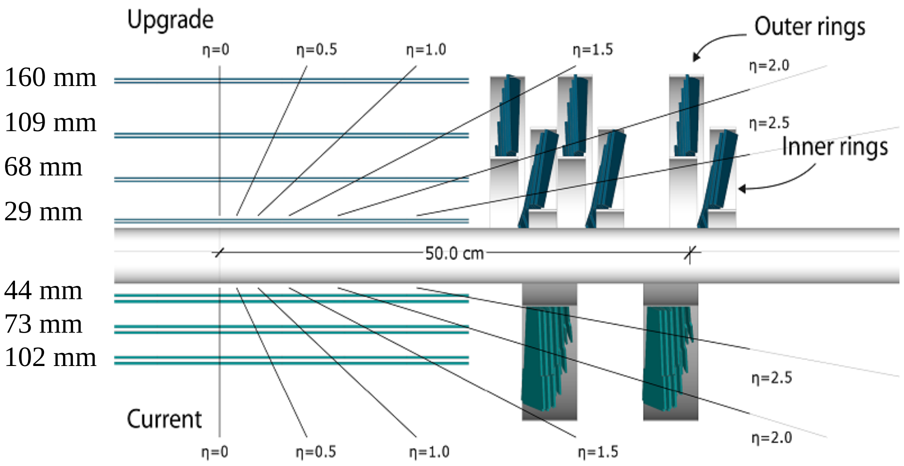






- Impact parameter measurement is highly determined by the pixel detector
- Much improved b-jet tagging capabilities at given light-jet fake rate
  - Heavy flavor tagging is important in Higgs precision measurements and in reconstruction of largely boosted objects
- Nearly twice as precise primary Z-vertex resolution in the longitudinal direction

The Phase 1 detector geometry concept



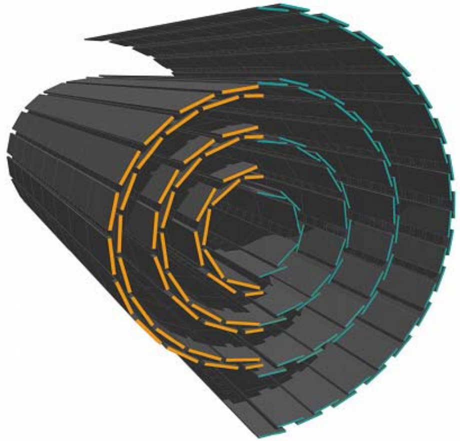
- Increase number of layers both in Barrel and Forward
  - Redundancy for hit loss
  - Quadruplet seeding possible
  - But total number of channels doubles (48 M to 79 M in Barrel, and 18 M to 45 M in Forward)

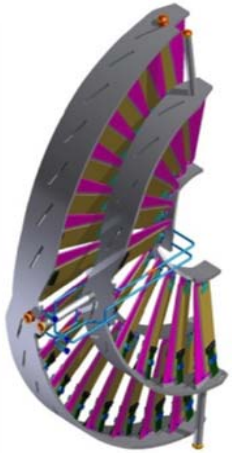
- Transverse resolution is improved in Forward pixel
  - Charge sharing increased by tilting the inner rings
  - Pixel size along the radius changes from 150 microns to 100 microns

- Inner layer moves closer to beam – better impact parameter resolution

- Outer layer moves closer to outer tracker – easier track propagation from seeds to first outer tracker layer

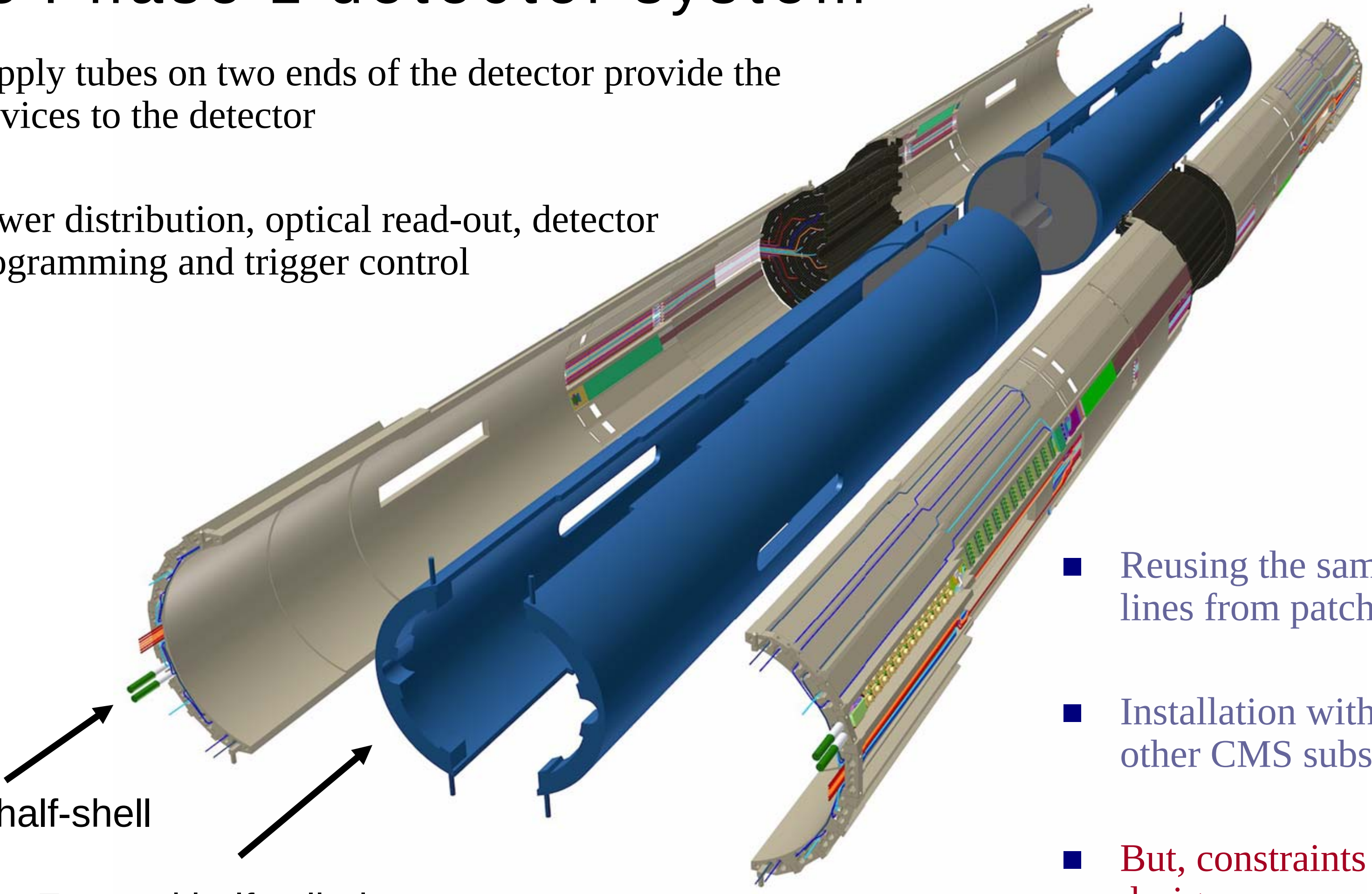
- Detector and services use the same mechanical envelope as the present system
  - Designed for quick replacement during extended TS in 2016





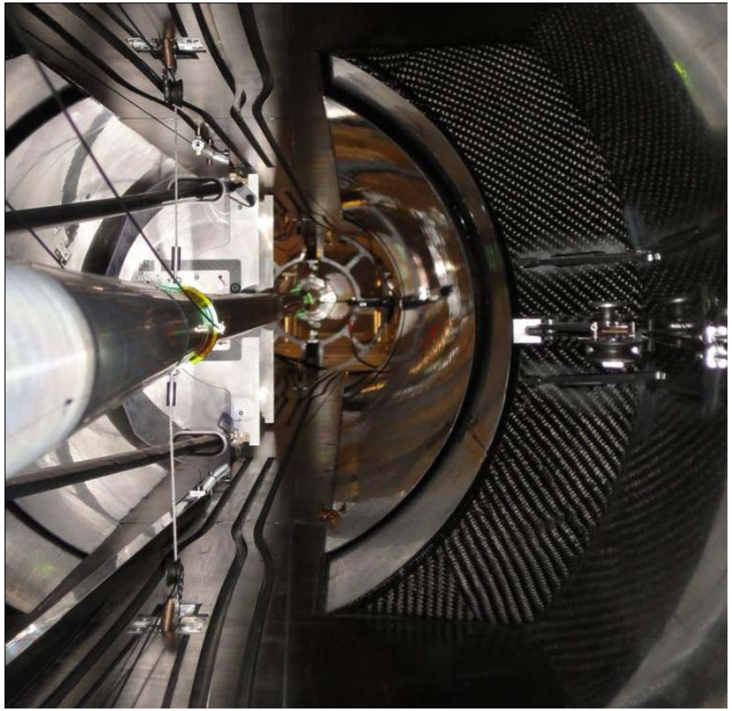
The Phase 1 detector system

- Supply tubes on two ends of the detector provide the services to the detector
- Power distribution, optical read-out, detector programming and trigger control



- Reusing the same power cables, fiber optic lines from patch panel
- Installation with minimum impact on the other CMS subsystems
- But, constraints imposed on electronics design

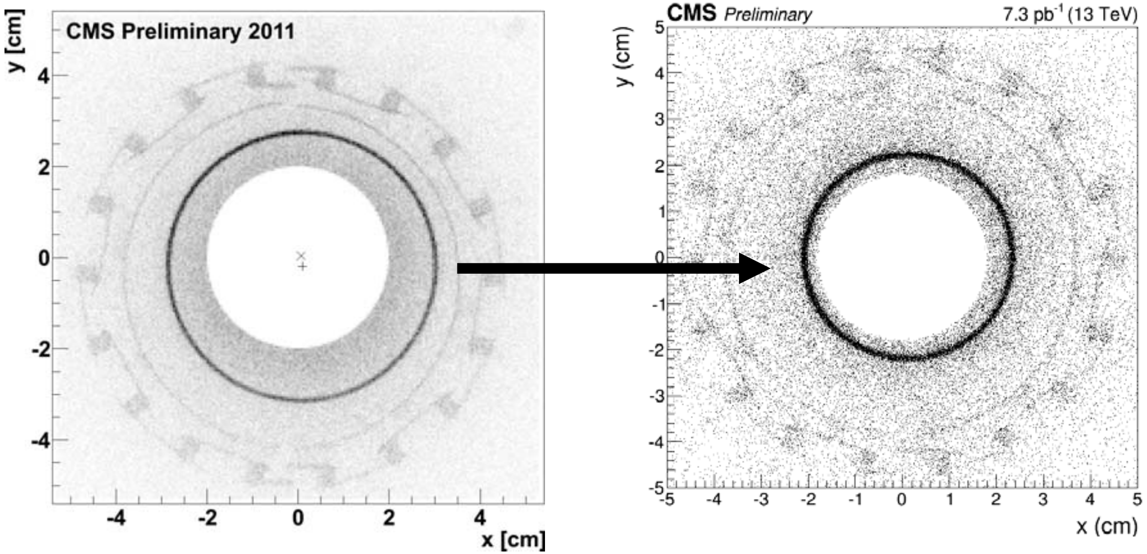
The Phase 1 detector system



- Inner layer is at smaller radius, requires more clearance
- Beam pipe changed from 59 mm to 45 mm during LS1

Barrel off-centered w.r.t beam pipe

Tracker material measurement

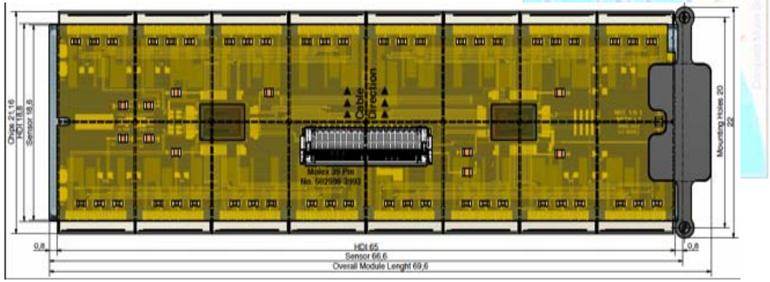


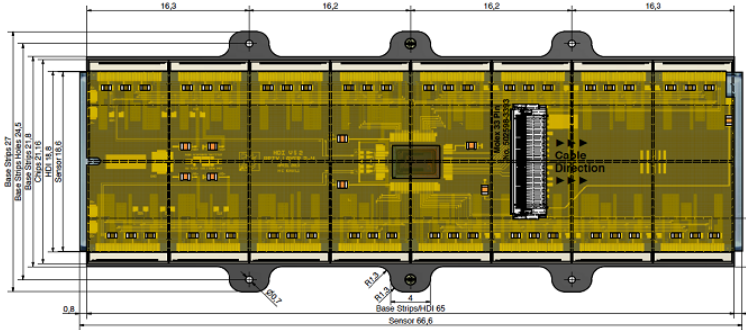
- Beam pipe position was checked in 2015 running
- Nuclear interactions reconstructed by tracking; multiplicity clearly shows beam pipe and Layer 1 of the current detector

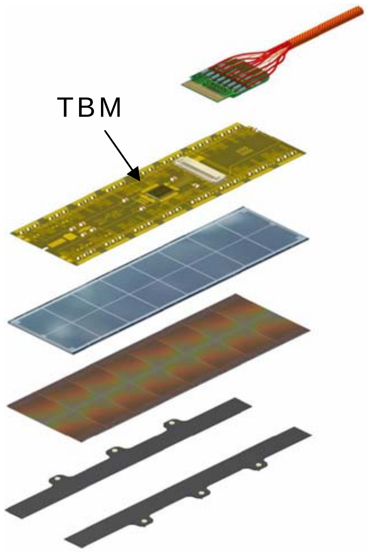
Module design for higher rate

- Modules made of 2x8 Readout Chips (ROC)
- Wire-bonded to 50 μm flex print high density interconnects (HDI)
- The Token Bit Manager (TBM) ASIC triggers and coordinates read-out of ROCs
- Serial readout at 160 MHz multiplexed to 400 Mbit/s throughput per channel

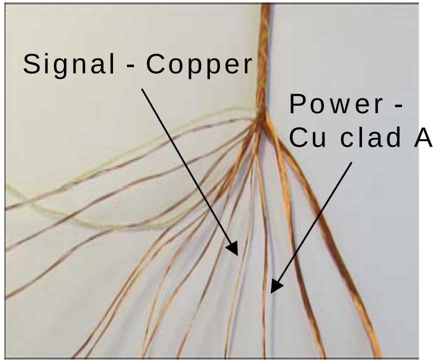
Layer 1:







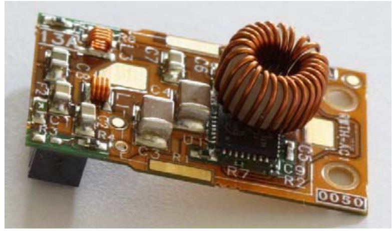
Twisted pair cable of BPix:



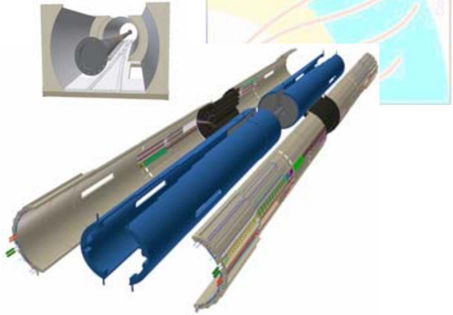
- Layer 2-4 modules are managed by single TBM – 8 ROCs in 2 channels for Layer 2 and 16 in Layer 3-4
- Layer 1 modules with dual TBM – 4 ROCs in 4 channels
- Transmission in 1 m twisted pair cables in Barrel, and 40 cm Al in Forward

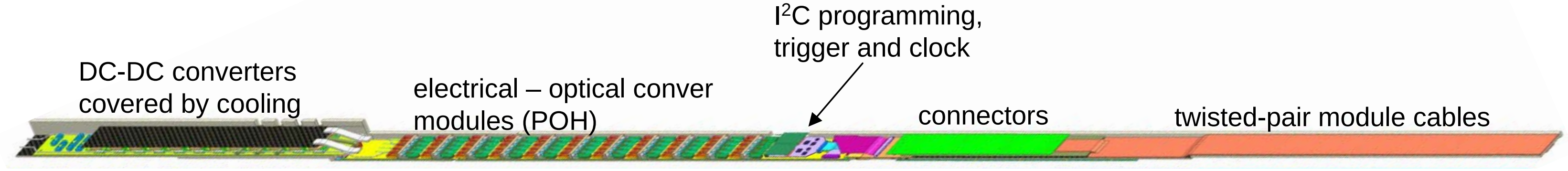
Powering and read-out

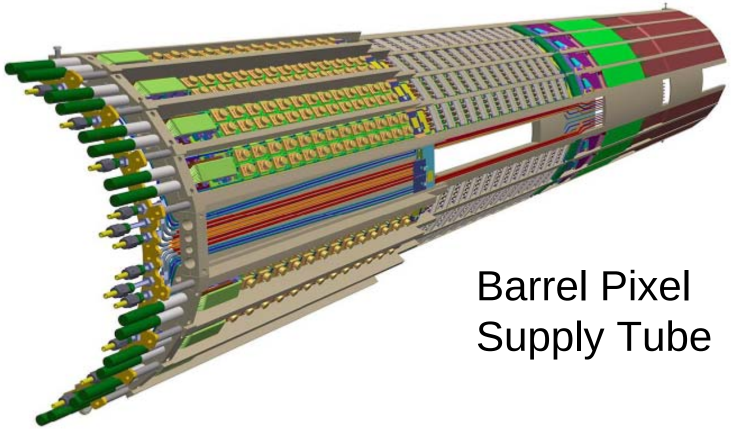
- Doubling the read-out is achieved with more modules, need more power
- Analog 3.0V and digital 2.5 V by DC-DC converters (80%) from 10 V input



DCDC converter with AMIS5 ASIC
(RF shield not mounted)







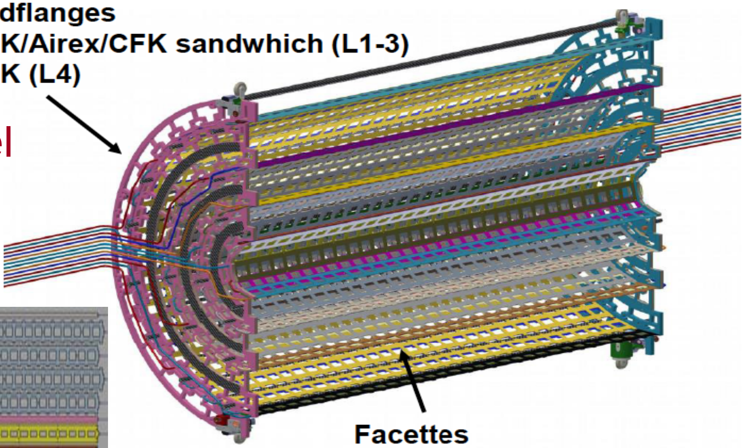
Barrel Pixel
Supply Tube

- Electronics
  - Distributes clock signal synchronized to TOF within 1 ns
  - Equally distributes data-load among back-end FPGA-s

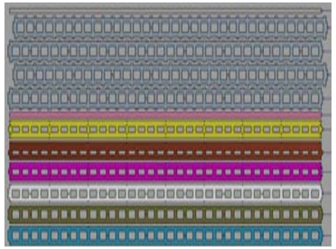
- 8 slots per half-shell, servicing a sector of up to 39 modules
  - 6 layers of 20 mm wide PCB-s and a bundle of 56 fiber optic cables stacked within a 20 mm deep slot

Mechanics and cooling

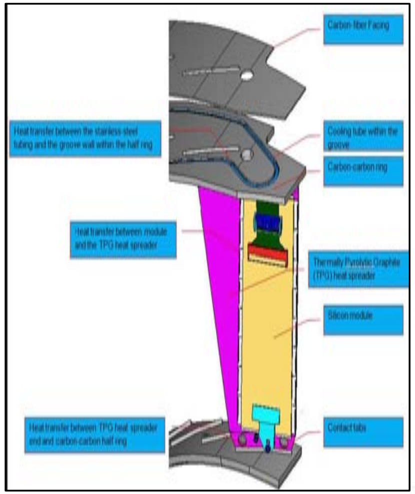
Barrel Pixel Mechanics



Facets for L1



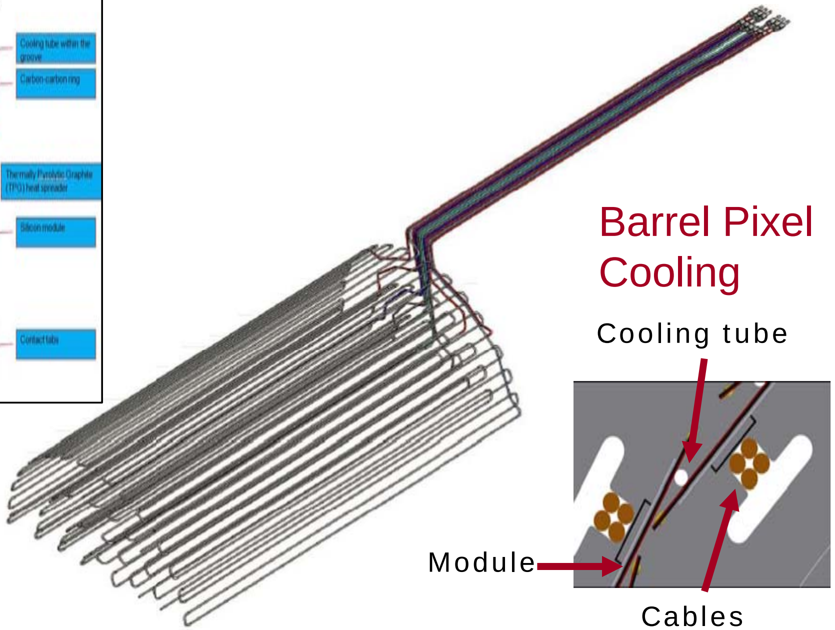
- Modules fixed to carbon fiber facettes by clamps (L1) and screws (L2-4)
- In Forward Pixel, cooling loops are embedded in graphite ring with CF cover



Forward Pixel

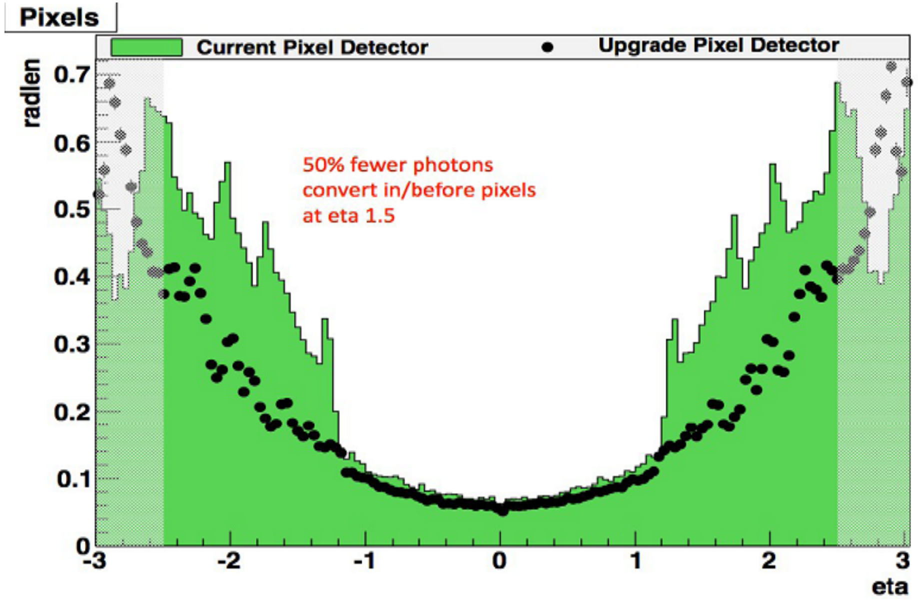
- C_6F_{14} cooling was replaced by evaporative CO_2
  - Higher load
  - Smaller cooling pipes with diameter 1.6 mm in active region
  - Expected to operate at T= -20 °C
- Also cools DC-DC converters and POH modules

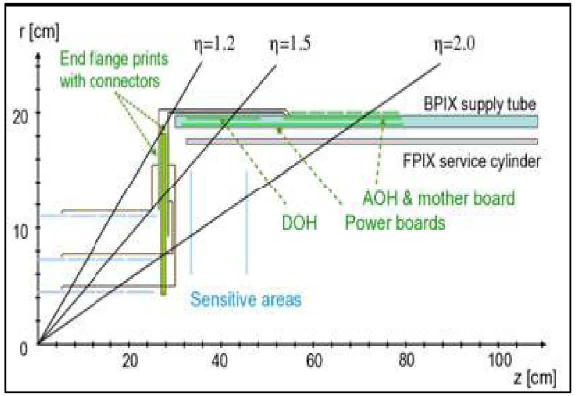
Barrel Pixel Cooling

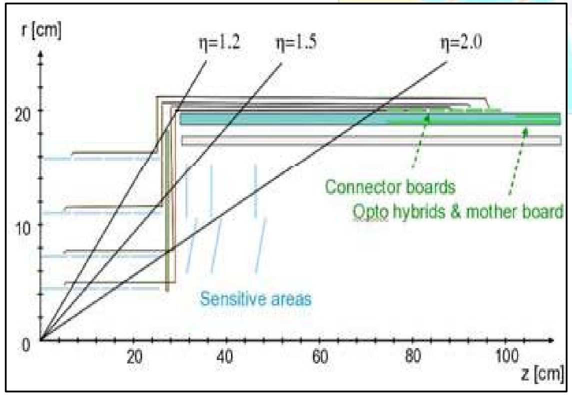


Material budget

- Light mechanical support
- Smaller coolant mass
- Supply tube has much more components, but shifted away from the interaction point





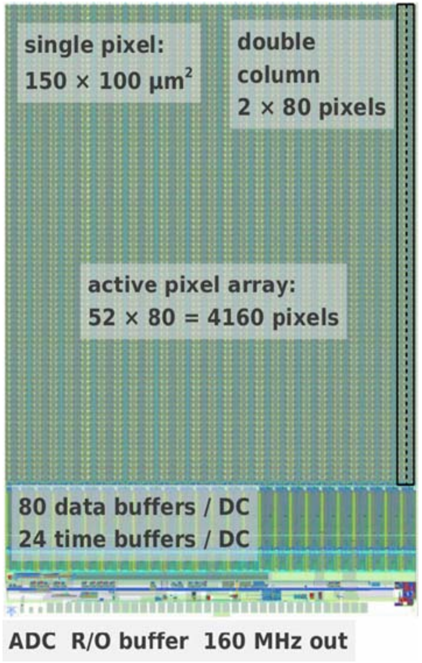


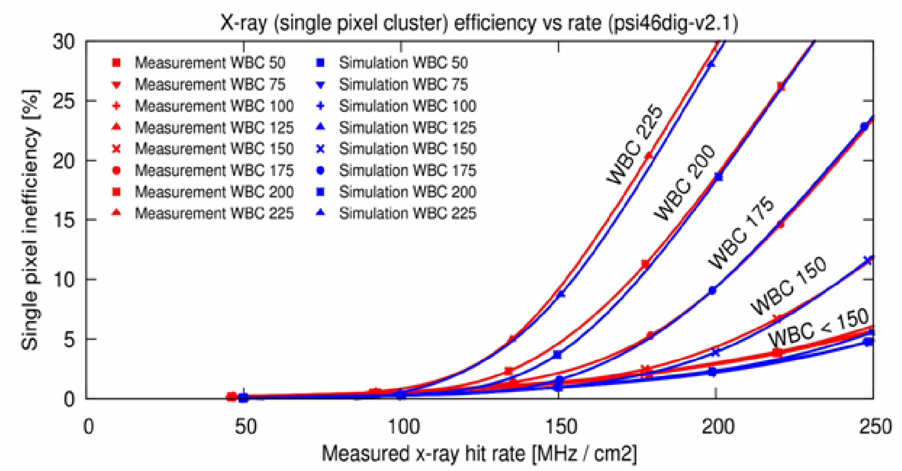
- Reduced mass, less multiple scattering and nuclear interactions
- Factor of two decrease in photon conversion between 1.1 and 2.6 in pseudo-rapidity w.r.t. current detector

The new ROC design

- New ROC is based on the present ROC design (PSI46) and technology

- Improvements
  - On-chip 8-bit digitalization
  - Lower threshold due to smaller cross-talk and improved comparator
  - Pixel hit buffer size from 32 to 80, Time-stamps from 12 to 24
  - Additional global readout buffer to reduce dead time

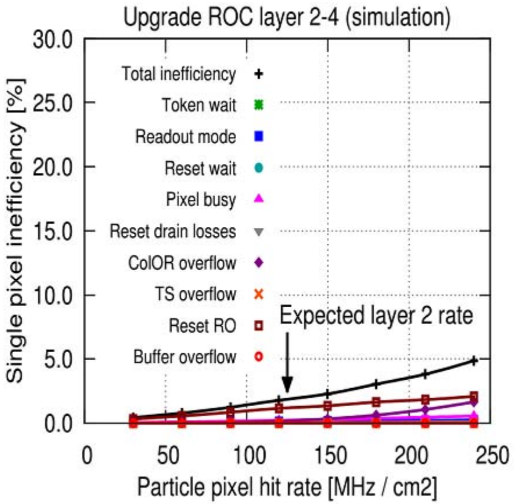


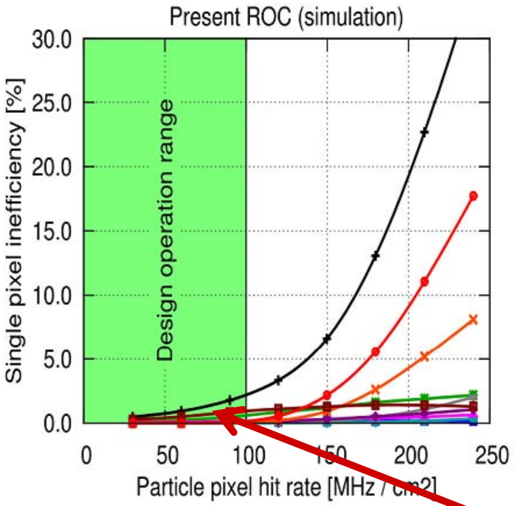


- Chip needs to buffer hits for the duration of the trigger latency
  - WBC setting in number or bunch-crossings
  - Present latency is WBC 168

- Simulation for upgrade ROC agrees well with X-ray measurements

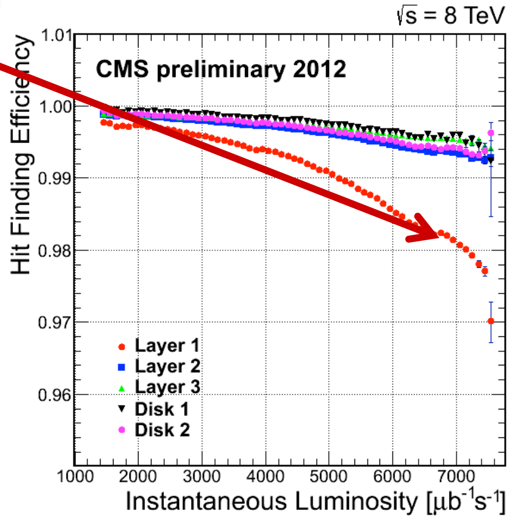
Hit efficiency

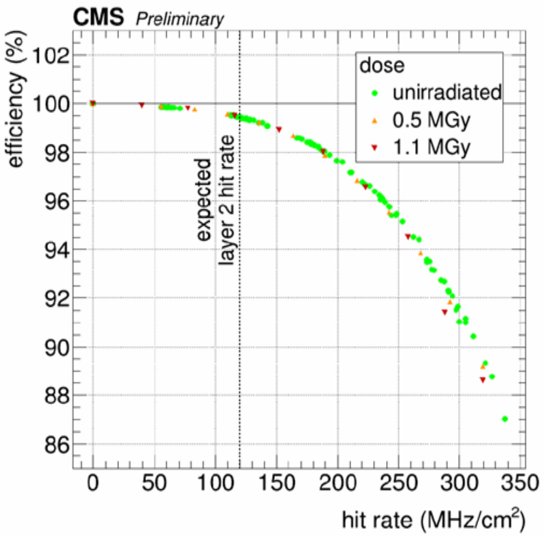




- TS and Buffer overflows, the major sources of inefficiency currently, entirely eliminated
- Typical expected rate 120 MHz Layer 2
- Chip to handle Layer 1 rate of 580 MHz is under testing

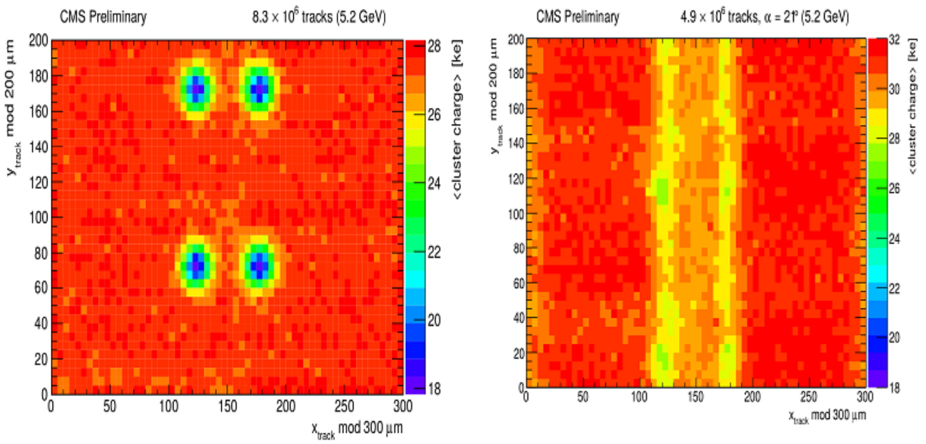
- Present detector operated at ~75 MHz/cm^2 in 2012
- 2-3% loss of measured hit finding efficiency, ~6-9% dcol loss – complicated relationship between beam test and real LHC conditions
- Performance of new Layer 2 chip is also expected to be stable with irradiation

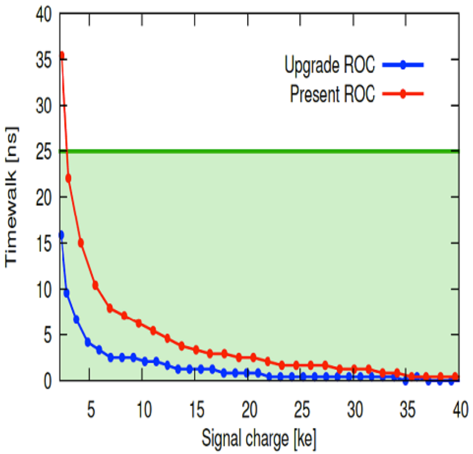


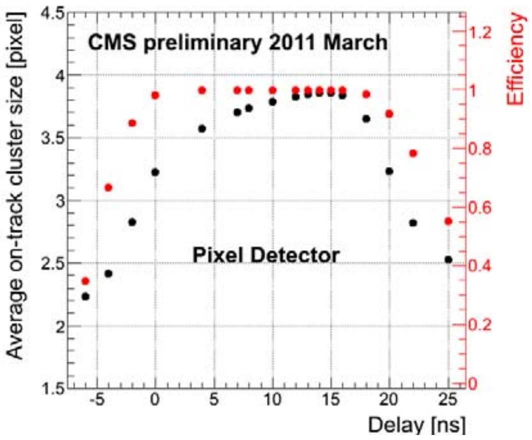


Module testing - Charge collection efficiency

- Cluster properties measured in test beam (at DESY with DATURA)
- Cluster charge
  - Large fraction lost at bias dot, otherwise uniform
  - Smeared out and reduced due to 21° impact angle set to mimic Lorentz drift
- Irradiation tests at KIT also showed full depletion below 600V after $4*10^{14}$ neq (for layer 2)

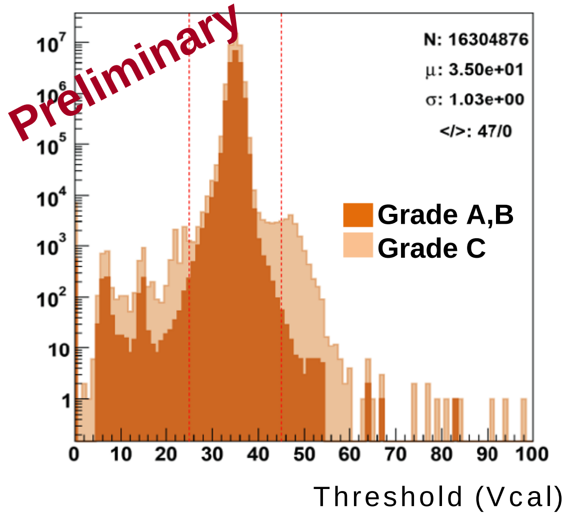


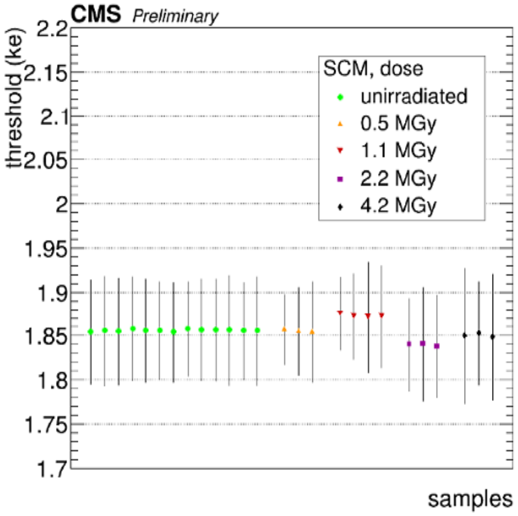




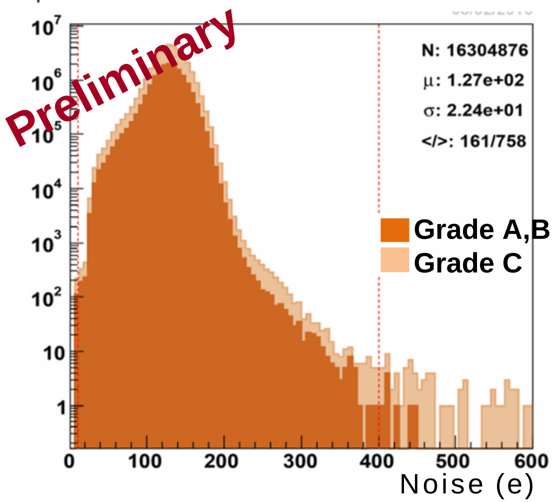
- Time walk effect is clearly visible in data taken at the LHC
  - Leads to „in-time" threshold higher than absolute one
- Long time walk results in loss of small pixel charges
  - Missing pixels in shoulders leading to loss in resolution
- Significantly reduced time walk with the new ROC

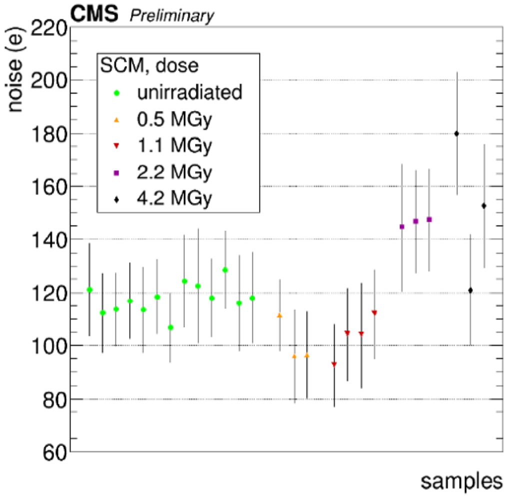
Module testing – Threshold and noise





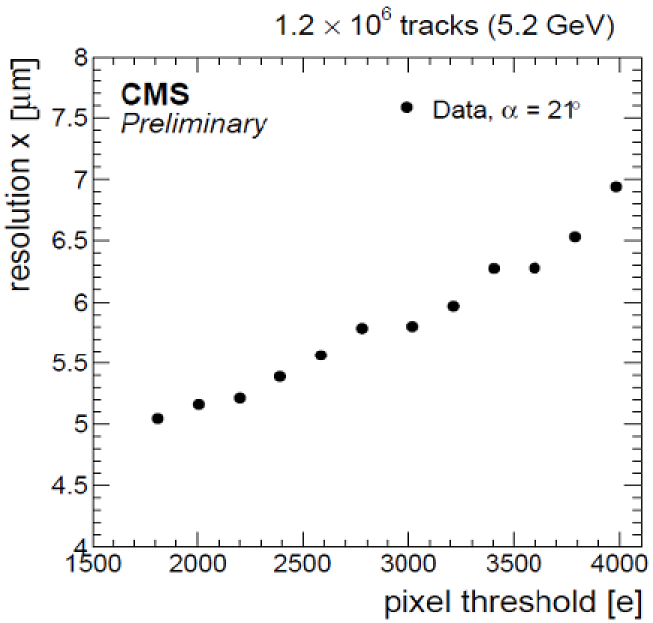
- Colors show results of grading (~90% bare and ~74% detector grade module yields)
- Average threshold ~1600 electrons (35 VCal units) from 3200 e
- Very stable with irradiation way beyond the dose expected after 500 fb^{-1} (1.2 MGy)
- Noise for modules qualified as detector grade (dark brown) much below threshold
- Noise stable with irradiation

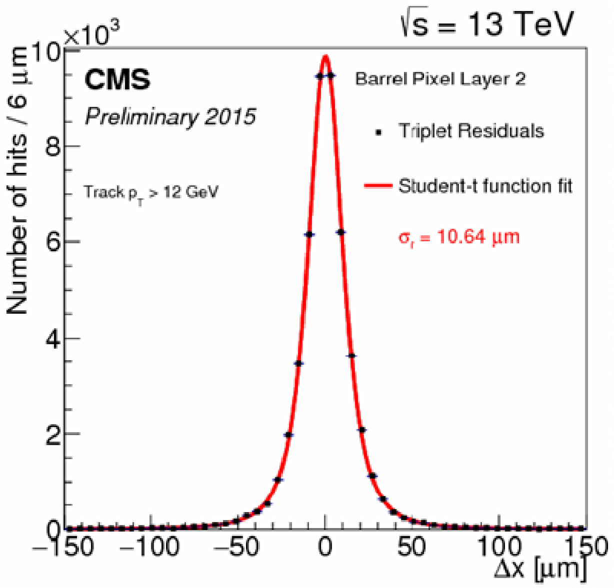


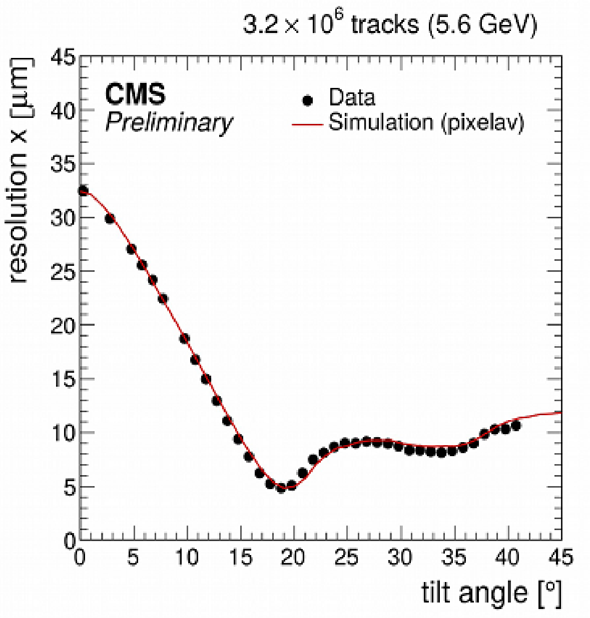


Resolution

- Cluster position resolution much better than pixel pitch due to Lorentz drift induced charge sharing
  - LA angle ~21°
- Lorentz angle decreases with higher bias voltage (moving the „wrong" way)

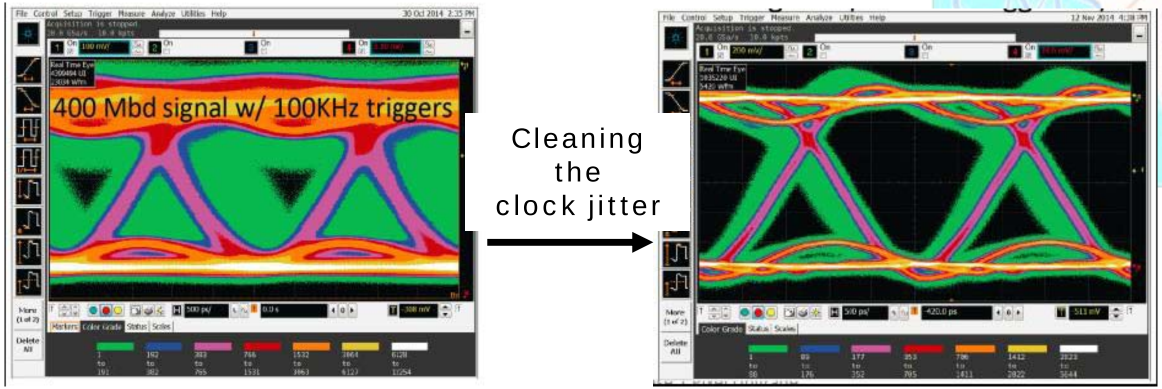






- Lower threshold beneficial effect is clrearly visible
- Improvements of cluster position resolution is expected from ~10.6 microns to 5 microns

Pilot System Tests



- Current Forward detector was designed to have 3 disks
- Extra space was used to construct a 3rd disk on the –Z side
  - 4 pairs (blades) of Phase 1 Forward pixel modules have been installed
  - 2 blades also use the new DC-DC converters allowing for realistic beam-test and SEU measurements
- Installation happened already in LS1, first data-taking at the end of 2015 during the HI run
- Integration into the CMS central DAQ provided useful exercise
  - It lead to the observation of an unwanted clock-jitter
  - Motivated a redesign in the control and read-out electronics, where an extra QPLL was introduced
  - Helped the development and testing of a new firmware on the back-end adjusted to the new digital readout

Status and Outlook

- The higher collision energy together with higher instantaneous luminosity also increases the demand towards the detector from the physics point of view

- The Phase 1 upgraded detector is expected to perform better than its predecessor due to several improvements
  - Smaller material budget
  - Improved hit coverage due to additional layer
  - Track interpolation between closer measurement points
  - Less efficiency loss at high rate
  - Lower threshold

- The beam test measurements and irradiations tests show very promising results

- The production of the new detector is progressing well in general, but a challenging year is ahead of us

- Pilot system already installed at the LHC provides tool for testing the new system, and allow for smooth exchange of detectors