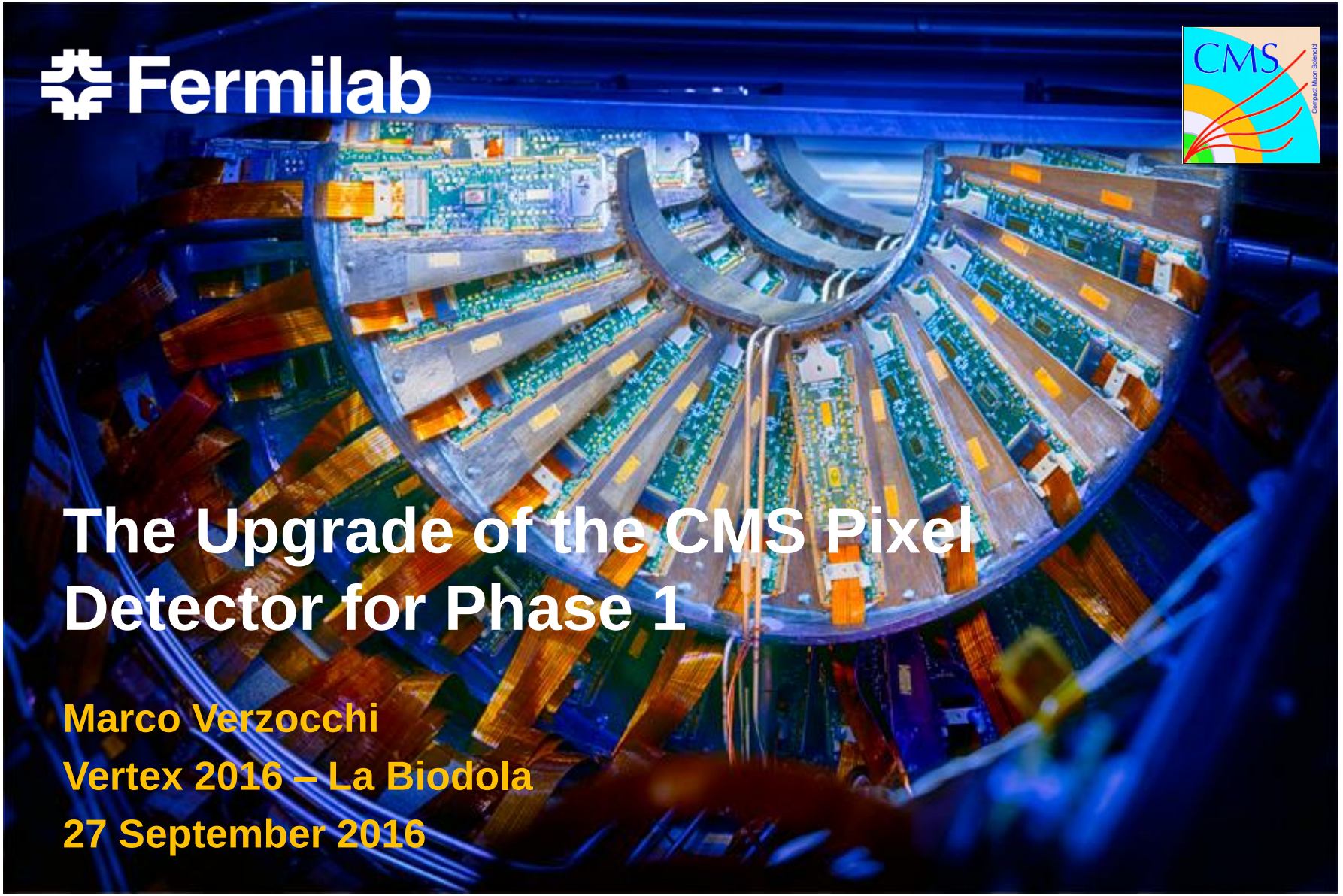


The Upgrade of the CMS Pixel Detector for Phase 1

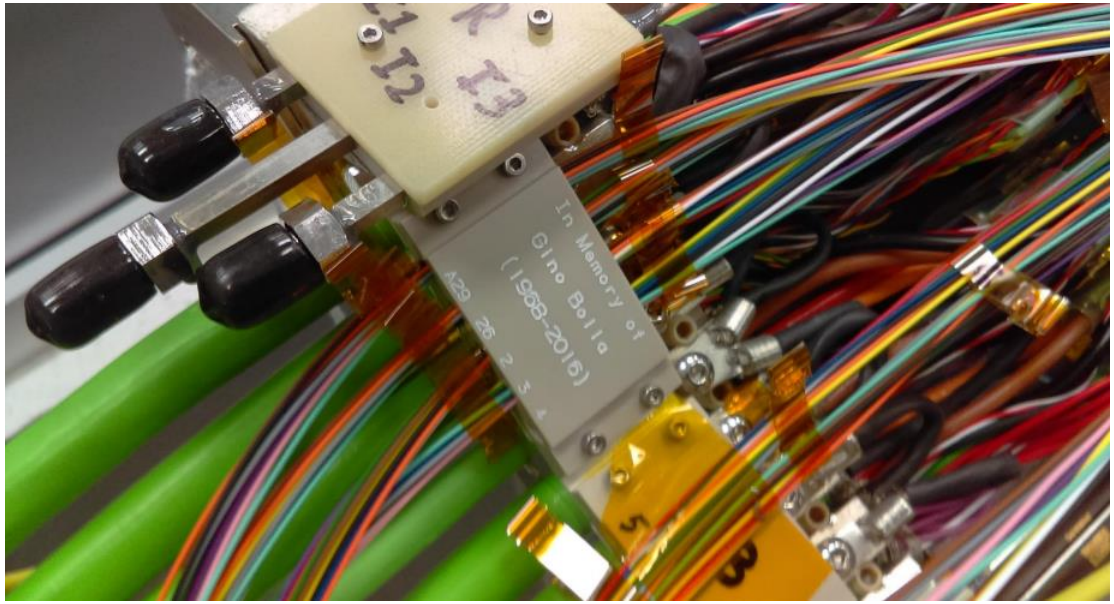
Marco Verzocchi

Vertex 2016 – La Biodola

27 September 2016

Outline

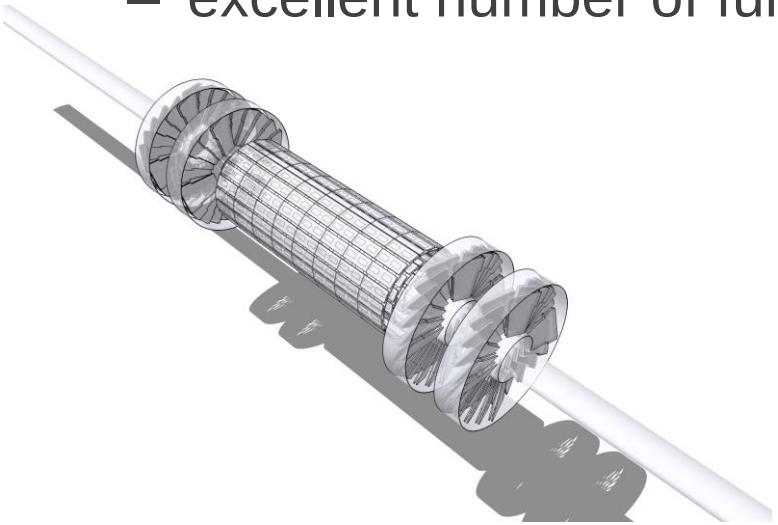
- The need for a new pixel detector for CMS and the design considerations
- Components for the new detector
- Construction status
- Plans for the next few months

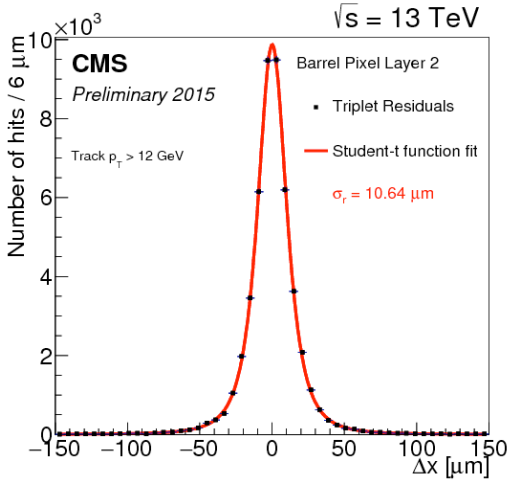


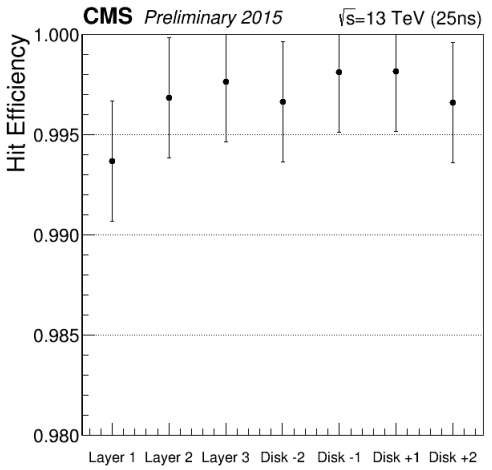
Fermilab

The Current Pixel Detector

- 66M channels, 3 position measurements along tracks
- First tracking layer: 4.4 cm radius
- n^+ in n sensors with pixel size of 100 x 150 μm^2
- Excellent performance:
  - resolution 10 µm (rϕ) 20-40 µm (z)
  - high efficiency (> 99%),
  - excellent number of functioning channels and uptime

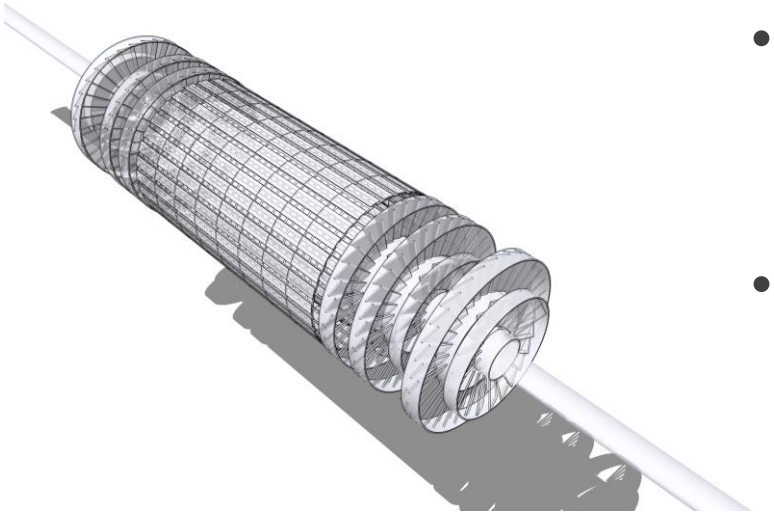






Reasons for Replacing the Current Detector

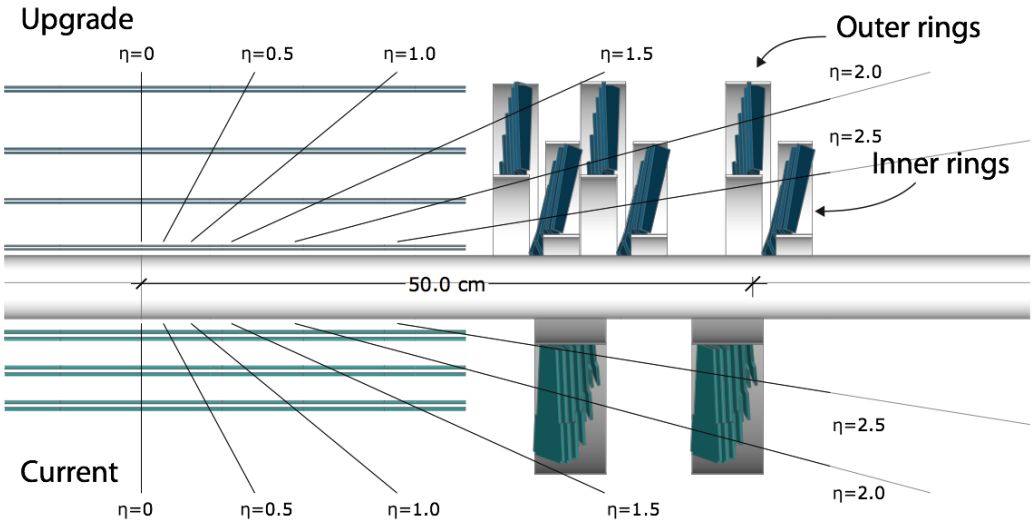
- Current detector designed for $L=10^{34}cm^{2}s^{-1}$, 25 ns bunch spacing
- LHC has already exceeded this instantaneous luminosity and may reach 2 $x10^{34}cm^{2}s^{-1}$ before LS3
- Dynamic inefficiencies / dead time caused by insufficient readout limited size of buffers / bandwidth of readout affect detector performance for L to >1.6 x $10^{34}cm^{2}s^{-1}$



- New beam pipe installed in LS1 can accommodate first layer at smaller radius
- Need to compensate efficiency losses in outer tracker due to radiation damage as L_{int} increases

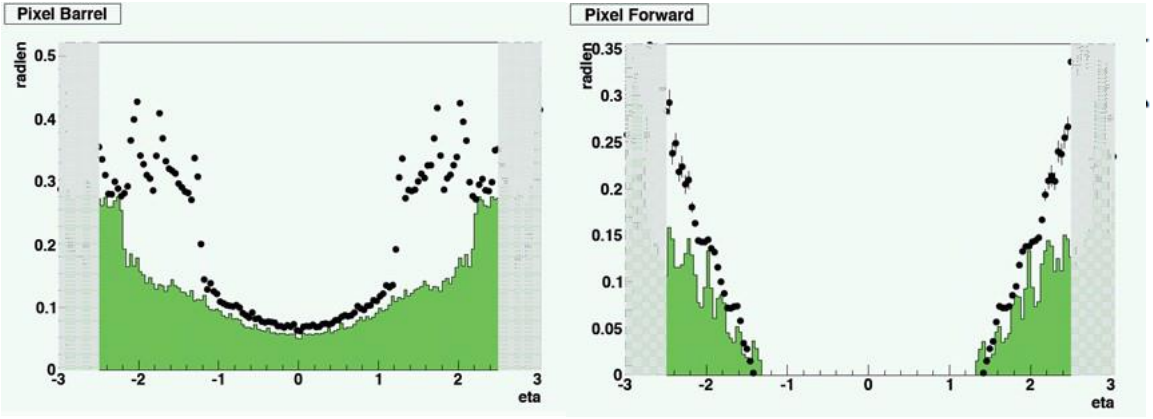
The Phase 1 CMS Pixel Detector

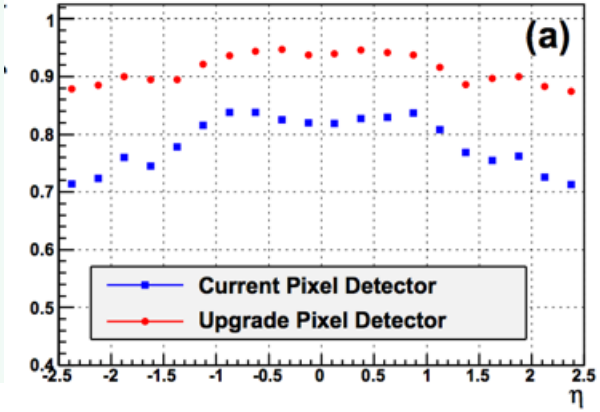
- Detector designed for installation in extended end of year shutdown, reuse as much as possible existing infrastructure, minimal impact on data taking
- Sensor & ROC technology, pixel size unchanged
- Improved ROC to recover hit efficiency
- Additional layer, first tracking measurement at lower radius
- Reduce material (lighter structures, CO_2 cooling, move to higher $|\eta|$)
  - Improvements in tracking efficiency, vertex resolution and b-tagging efficiency



Detector Improvements & Impact on Performance

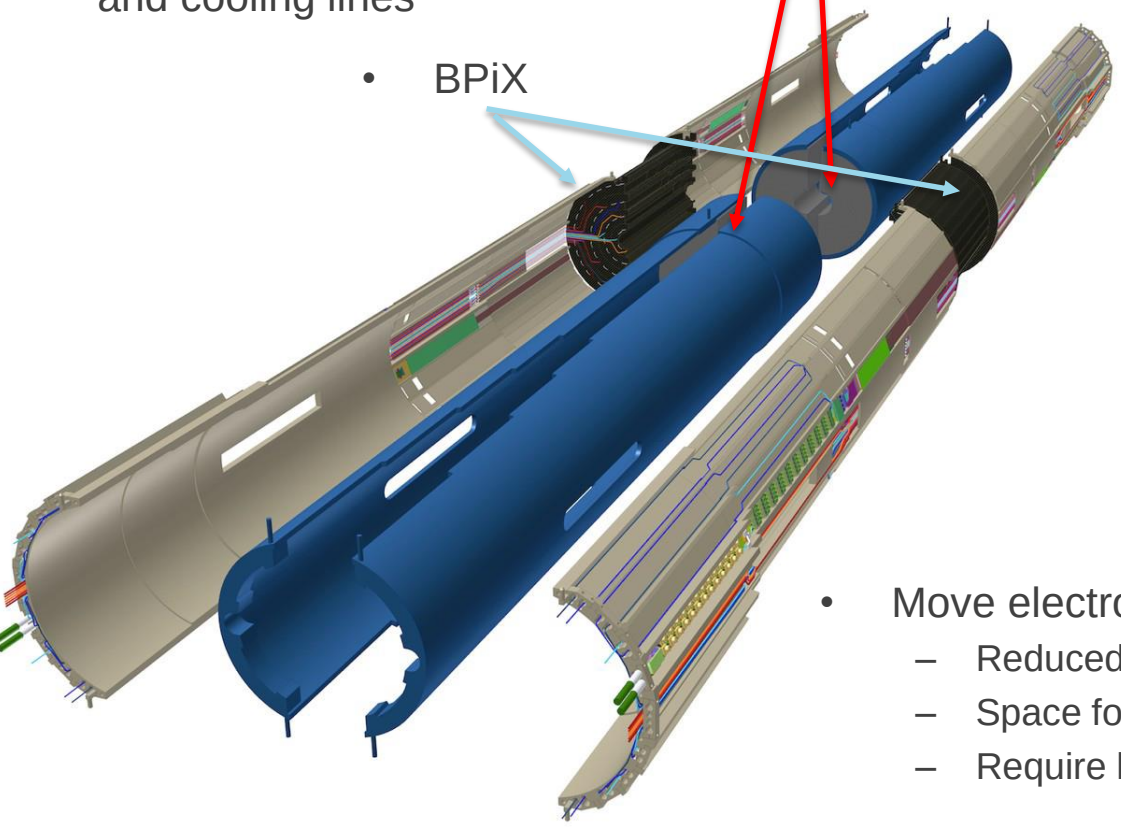
- Additional tracking layer reduces combinatorics
- Improved digital ROC with larger readout bandwidth and buffers
  - Retain high tracking efficiency even for pileups of 70 events (L = 2 x$10^{34}$$cm^{2}s^{-1}$)
  - Reduce number of fake tracks
- Keep material in tracker sensitive volume ($|\eta|<2.5$) at the same level (or better) compared to current detector even with significant increase in number of channels
  - BPiX 48M → 79M, FPiX 18M → 45M
- Significant gains in terms of effective luminosity (factor 2 for some analyses)

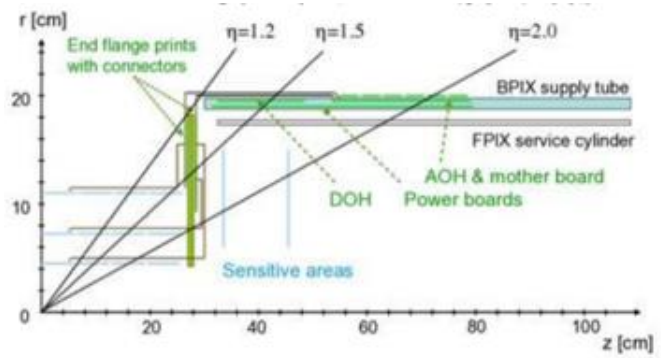


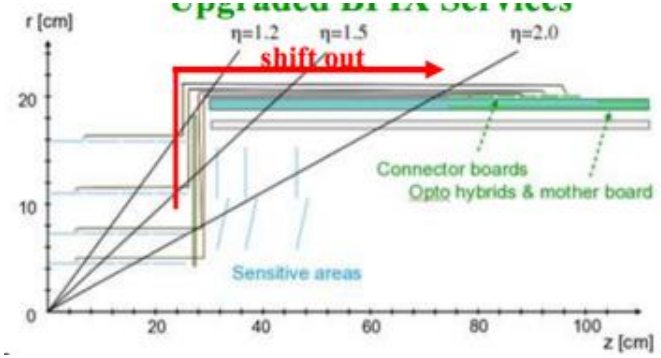


The CMS Pixel System

- Service cylinder (FPiX), supply tube (BPiX) host power, readout electronics with optical converters and cooling lines



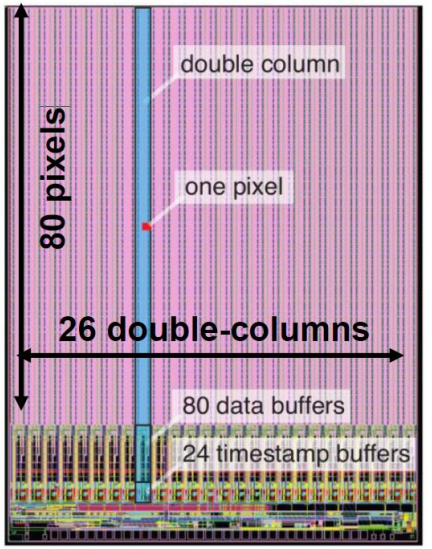


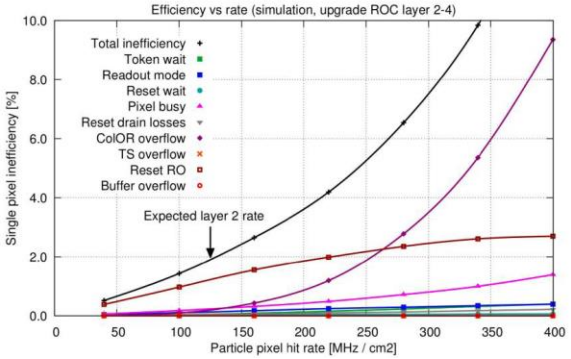


- Move electronics away from interaction point
  - Reduced mass in tracking volume
  - Space for more extensive FPiX system
  - Require long (~1m) cables to read out modules

Readout Chips (i)

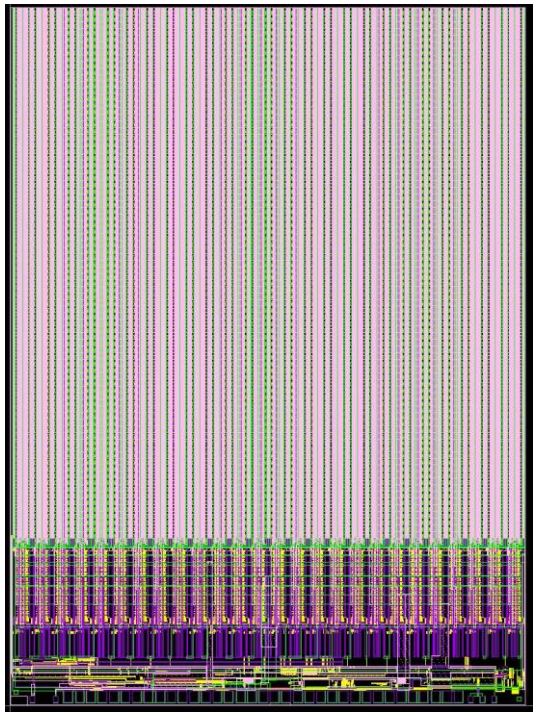
- New readout chip based on present PSI46roc
- Same technology (250 nm CMOS) and column drain architecture
  - 40 MHz analog 160 Mbit/s digital (8 bit ADC)
  - Increase of hit (32 → 80) and time stamp (12 → 24) buffer depth
  - Additional readout buffer
  - Smaller cross-talk, improved comparator
    - Threshold reduced from 3200 e^- to 1800e^-, better efficiency, resolution & longevity
- Final version for BPiX L2,L3,L4 & FPIX performing very well (max hit rate 120 MHz/cm^2)
  - Insufficient for operation in L1 (rate 580 MHz/cm^2)





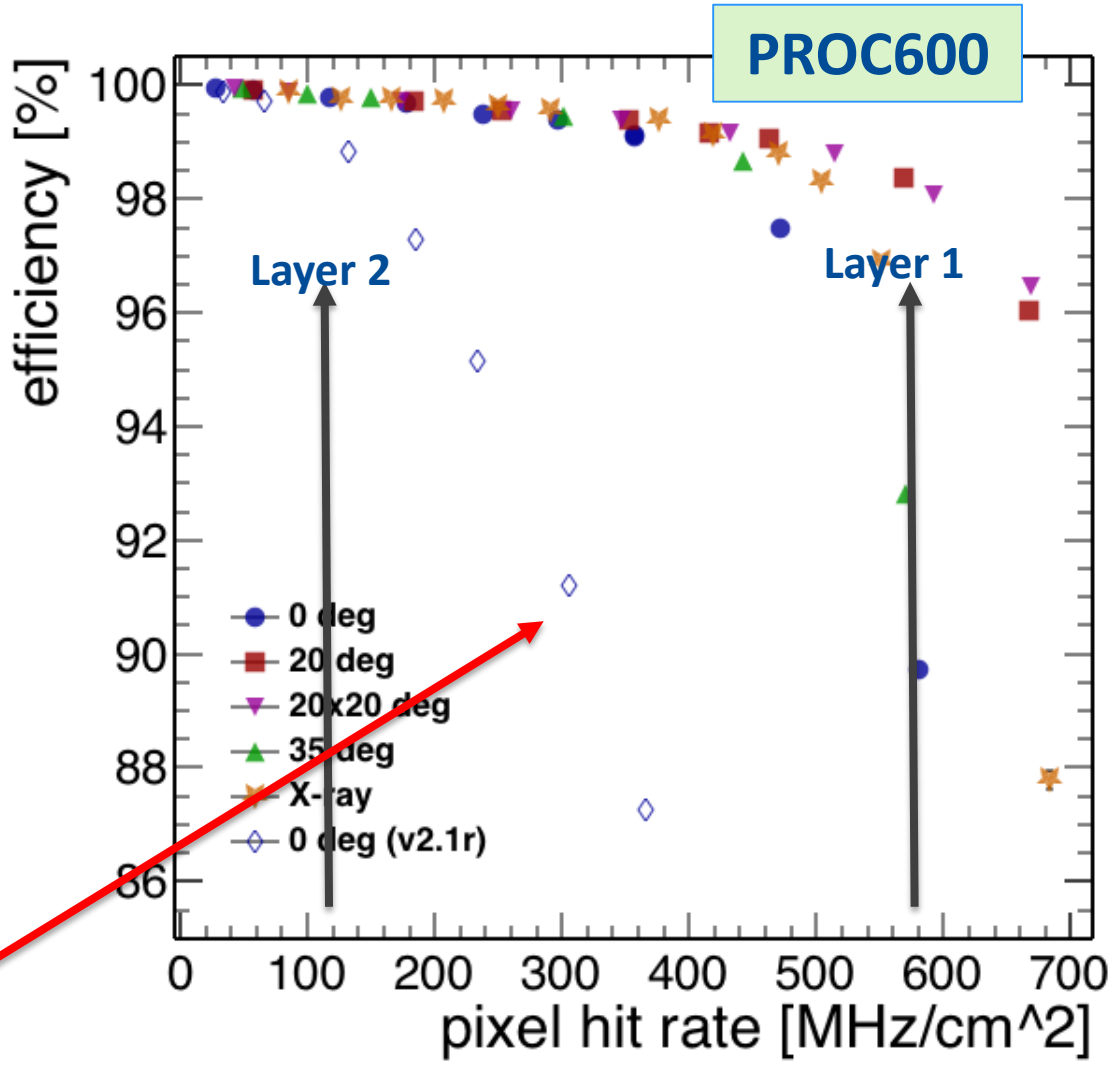
Readout Chips (ii)

- New readout chip (PROC600) with additional increased buffers
  - Same pixel size, same 250 nm technology
  - Requires additional space on the periphery, chip 3% larger
- Layer 1 requires gain in speed: readout clusters of 4 pixels instead of single pixel (dynamic cluster column drain)
- New chip can sustain hit rates of 600 MHz/cm^2
- Radiation hard to 500 MRad (> 1 ab^{-1}), no need to replace Layer 1 half way through data taking after LS2
- 1 design iteration, final version wafers delivered in June, decision to build Layer 1 at the beginning of August



Readout Efficiency

- Inject known charge in pixels in environment with high hit rate
  - X-rays (single pixel clusters)
  - Proton beam
    - Small inefficiencies at rates seen in Layer 1



Layer2-4 + BPIX readout chip

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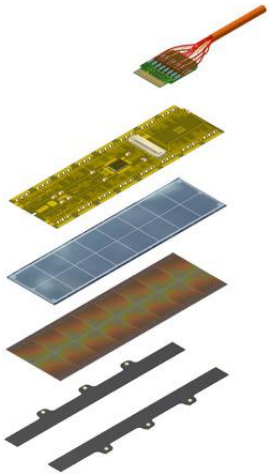
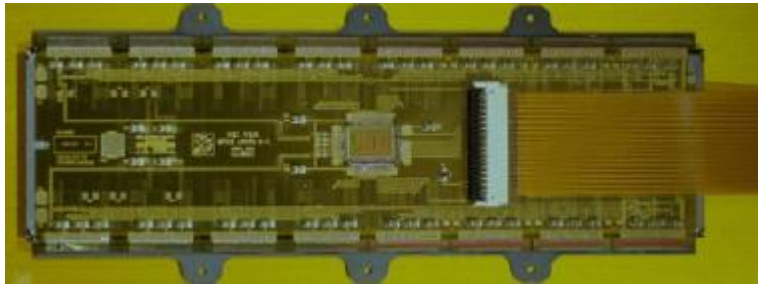
Detector Modules

- Sensor + 16 ROCs + HDI with token bit manager(s) and readout cable
  - 66k pixels per module
- 5 production chains (BPiX), 2 identical production chains (FPiX)
- Mixture of in-house / vendor based solutions for bump bonding
- 1856 modules for BPiX, 672 for FPiX



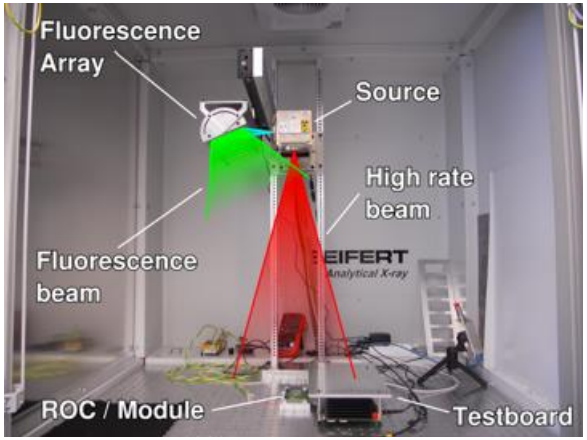
L1+L2: Switzerland
L3: CERN+Finland+Taiwan / Italy
L4: 2 German production chains
FPiX: USA

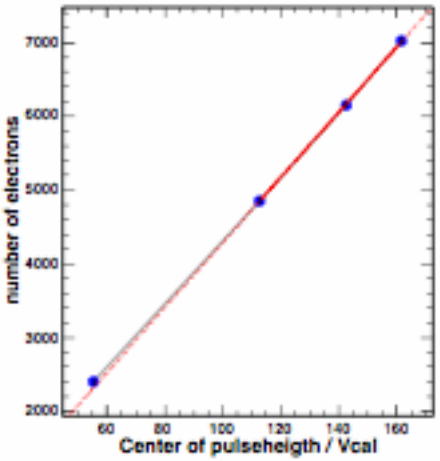


Fermilab

Module Qualification

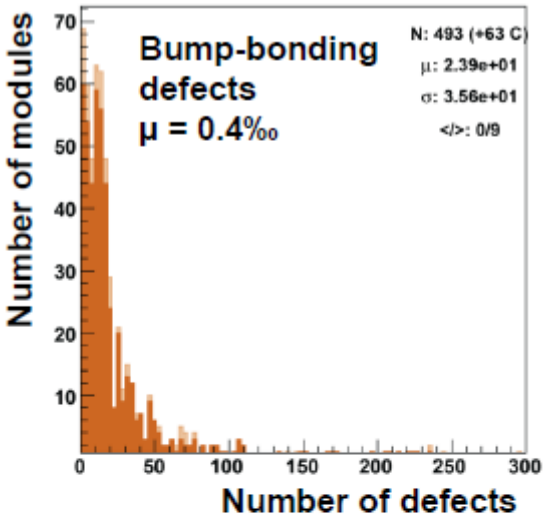
- Test procedures, analysis software, grading criteria common to all production centers (BPiX), minor modifications for FPiX
- Thermal cycles to eliminate detectors with poor bump bonding
- Detectors qualified both at room temperature and at -20C
- Measure IV curves and calibrate each ROC
  - Grading based on leakage current, number of pixel defects, noise, ….
- Tests with X-rays
  - Check performance at high rate (ROC periphery not fully tested during wafer probing)
  - Absolute energy calibration with fluorescence lines

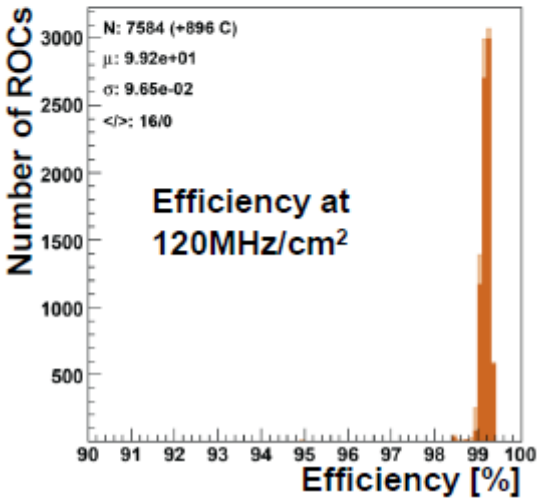




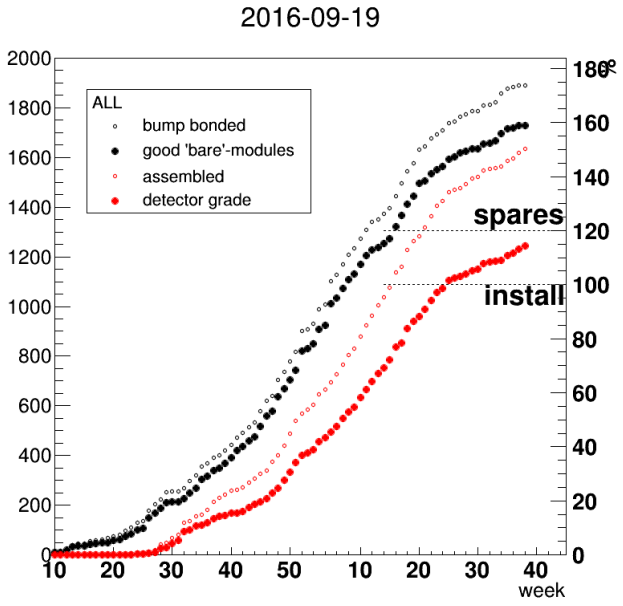
Fermilab

Module Production - Barrel



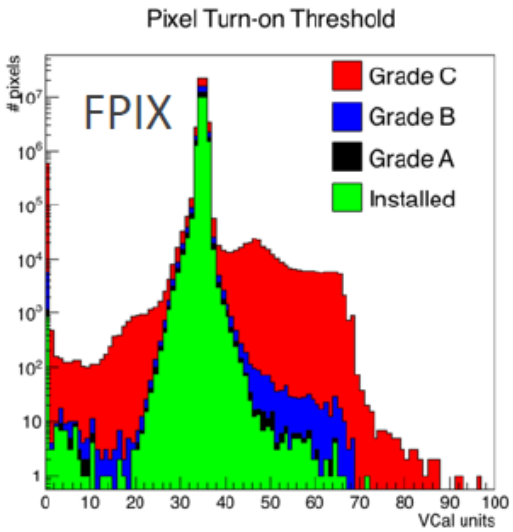


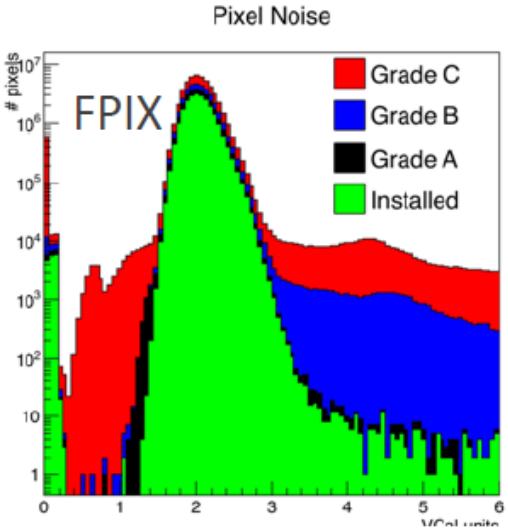
- Enough modules in hand for L3/L4
  - Production of spares continuing
- Production of modules for L2 to be completed next week
- L1 modules completed mid October

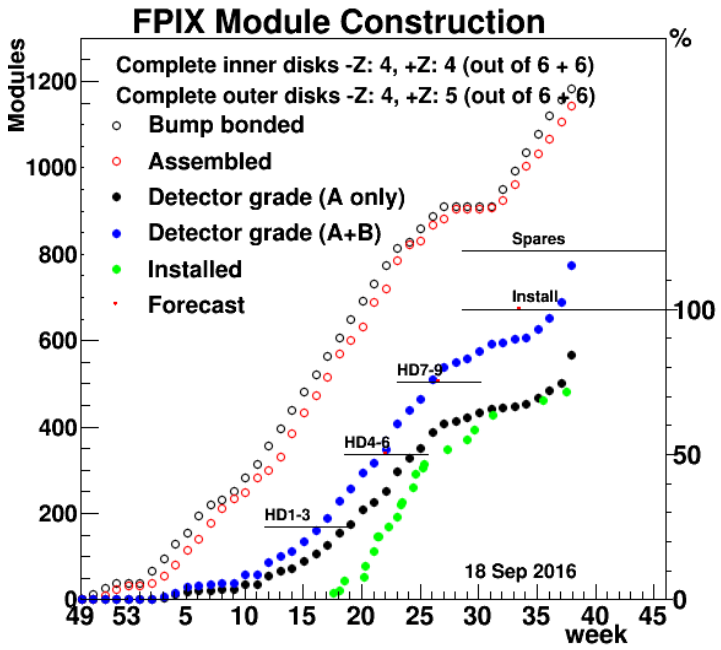


Module Production - Forward

- Production almost complete
- Module qualification to continue until mid-October
- Lower yield compared to BPiX (no bare module testing & rework, additional 10% yield loss)

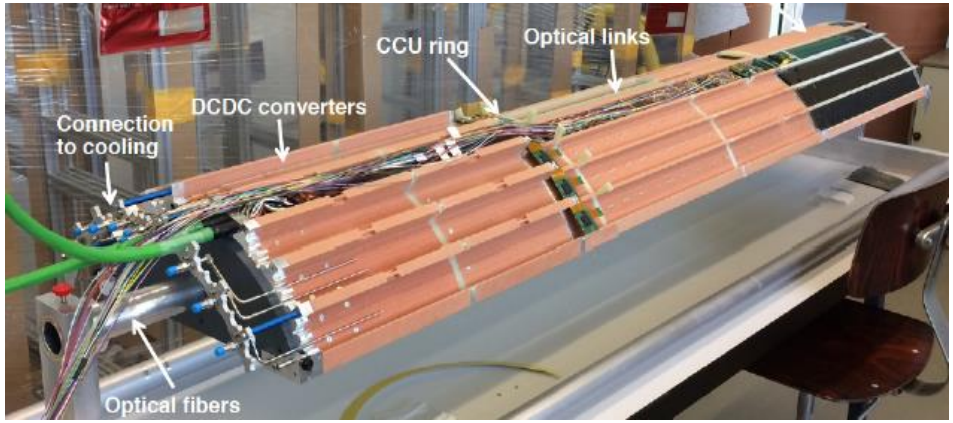






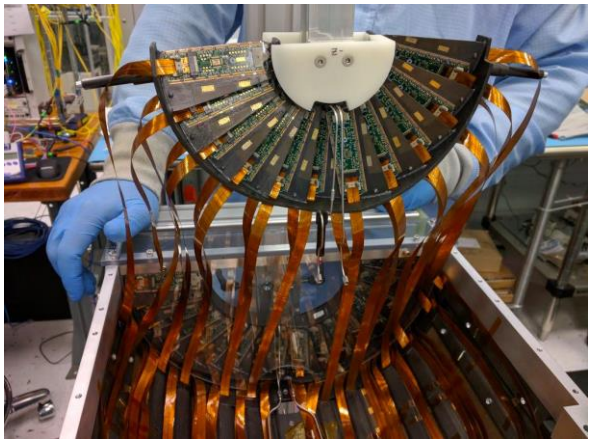
Mechanical Supports - Barrel

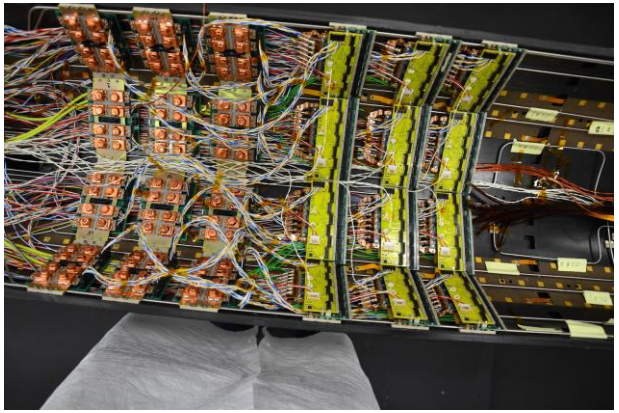
- Lightweight support structure made from CFRP/Airex compound for the barrel,
- Cooling tubes are the backbone of the structure
- L1/L2 half shells ready with cooling pipes embedded
  - Module mounting started for L2
- L3/L4 in preparation
- Supply tubes ready and electronics installation / testing ongoing



Mechanical Supports - Forward

- Service half cylinders complete, first 3 fully equipped with electronics, final one complete this week
- All 12 inner and 12 outer half disk complete with tubing embedded, 482/672 modules installed (9 outer half disks + 8 inner half disks)
- All half disks installed in first 2 half cylinders, 2 outer + 1 inner half disks installed in 3rd half cylinder
- After testing, disks removed for transport to CERN





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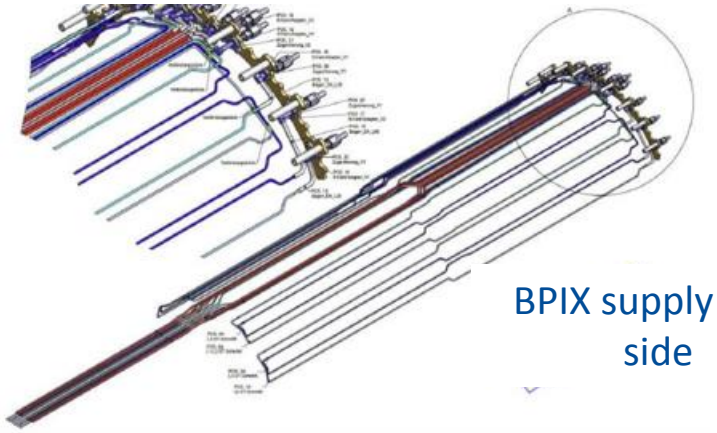
Cooling

- Moved from single phase C_6F_{14} to two phase CO_2 at -20 C
  - Heat removed through latent heat more effective
  - Higher pressure smaller pipes less material



BPIX supply tube side

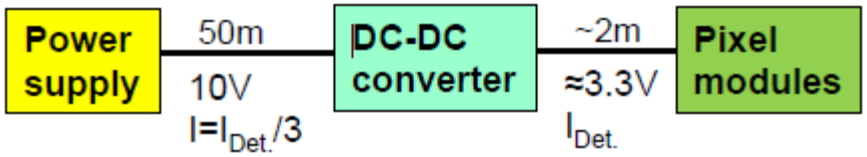
BPIX detector side

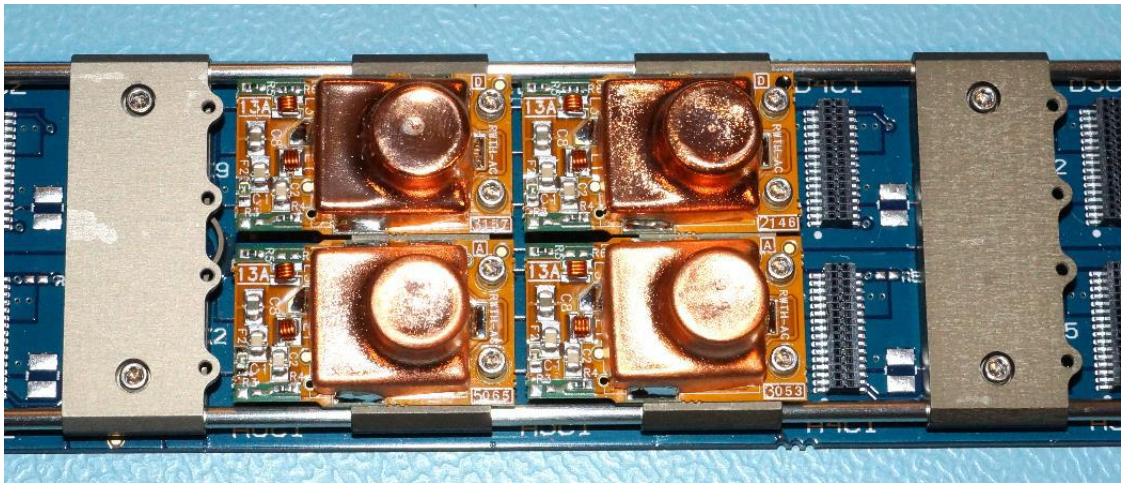
- In the detector part stainless steel pipes with inner diameter in the 1.7-2.3 mm range, 50-100 um wall thickness

- Bending (BPiX) and laser welding (FPiX) have been a source of concerns and delays

Powering

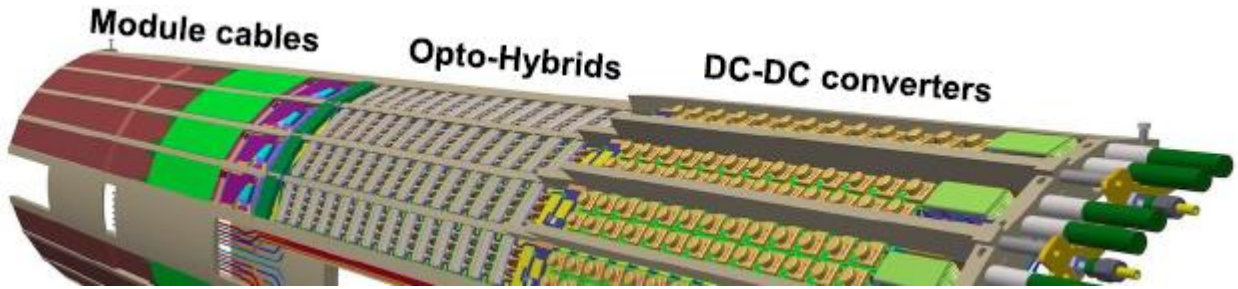
- Factor 1.9 more channels, losses in cables factor 4 larger
  - Cannot power detector with present cables / power supplies
- Use DC-DC converters





- Custom DC-DC boards using CERN FEAST2 ASIC
- Power efficiency > 80%, good performance
- 1200 DC-DC converters in total

Ancillary Electronics



- Distribute power (through DC-DC converters) and bias voltage to the modules
- Receive and distribute fast I2C-like signals for configuring ROCs and TBMs
- Receive and distribute clock, trigger and control signals
- Convert signals from modules from electrical to optical

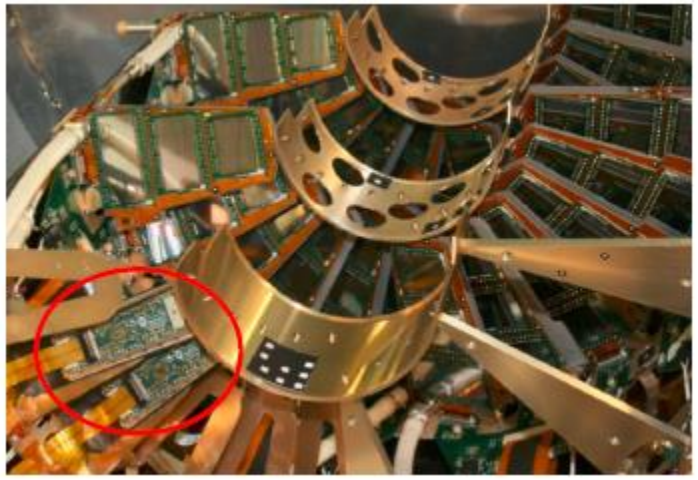
- Different solutions, same ASICs, optical Tx and TRx
  - BPiX: printed circuit boards embedded in slots in the supply tube, very little wiring
  - FPiX: discrete printed boards with different functionalites connected by wiring
- Electronics (DC-DC converters) act as a preheater for the CO2 cooling to force the transition into two phase operations

µTCA DAQ

- Two types of boards
  - FED – receive data from detector, send them to readout / HLT
  - FEC – send / receive control signals to the detector (clock/trigger/controls distributed via CCU, fast IC2-like signals for configuring modules)
- Both boards based on FC7 µTCA card with different flavors of mezzanine
- Procurements almost complete, burn-in tests ongoing

Pilot System

- DAQ development helped by availability of a 0.5% system already installed in CMS “the pilot system”
  - Uses prototypes of FPiX components
  - VME backend (but some sharing of firmware between µTCA and VME cards)
  - Now routinely in global data taking with VME system, working on µTCA system



- Gain operational experience under realistic conditions, even if limited number of channels available
- Helped spotting some problems in the control chain electronics that has informed board design

Integration Tests

- FPiX
  - first two half cylinders with all the half disks at CERN this week, first one reassembled and ready for testing
  - Second pair of half cylinders will arrive in November
  - Entire half cylinder tested cold (-20C) at Fermilab with final readout, controls and powering chains
  - Detector tested again and fully calibrated at CERN (TIF) prior to transport to P5, second check performed at TIF prior to installation
- BPiX
  - Service cylinder electronics tested cold in Zürich
  - Test 1 sector at a time warm after connection to barrel in Zürich
  - Transport to CERN (late January / early February)
  - Keep open the possibility of cold tests at P5

Installation and Commissioning

- Old detector removed in January, new one installed at the end of Febraury / beginning of March
  - Some infrastructure preparation work done in LS1
  - Remove old cooling lines replace with new ones
- Once the detector is installed perform checks at 13-15C, then close the end caps, cool down, more tests and calibration, including collecting cosmics
  - Need ~2 weeks to be ready for data taking
- Data taking, first few stores
  - Timing of all subdetectors
  - Need 1-2 stores to get alignment for new detector
  - Start data taking…..

Summary

- CMS will replace its pixel detector in early 2017
- The new detector will allow high quality physics data taking until the HL-LHC upgrades
  - One additional tracking layer, higher rate capability, reduced material budget, lower operational threshold, reuses a significant part of the existing infrastructure (including power cables and fiber plant)
- Construction of detector nearing completion,
- Started delivery of components at CERN and integration tests

See the related poster by Simon Kudella

Many thanks to all the CMS Pixel Phase 1 Collaborators

Supplemental Material