ALICE ITS2 MAPS Detector Construction Experience

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on behalf of the ALICE experiment

Science and Technology Facilities Council

UNIVERSITY OF LIVERPOOL

ALICE Upgrades in LS2@LHC

Motivation:

High-precision measurements of rare probes at low p_T

- Cannot be selected by hardware trigger
- Need to record large minimum-bias data sample
  - Read out all Pb-Pb interactions up to the **maximum collision rate of 50 kHz**

Goal:

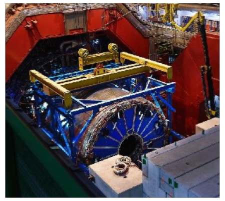
- Pb-Pb integrated luminosity 13 nb^{-1}
  (plus pp, pA and O-O data)

  -> Gain factor 100 in statistics for min bias sample

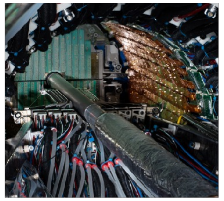
  w.r.t. runs 1+2
- Improve vertex reconstruction and tracking capabilities

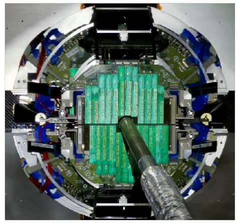
Strategy:

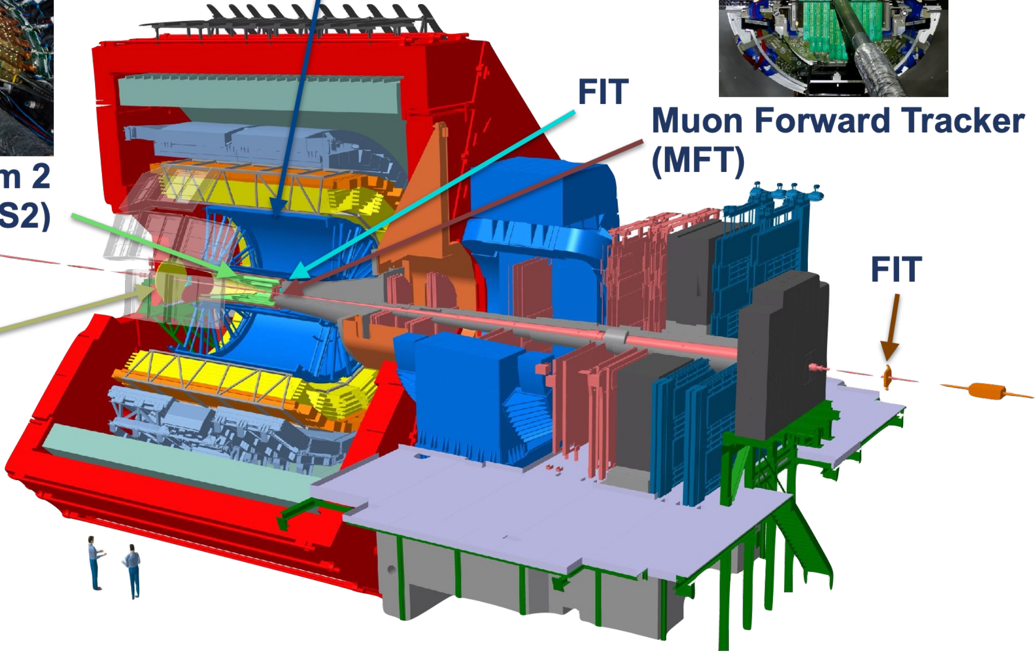
- new ITS, MFT, FIT, TPC ROC
- update FEE of most detectors
- new integrated Online-Offline system (O^2)

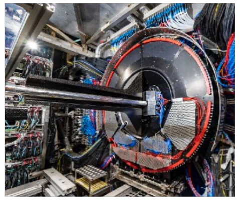


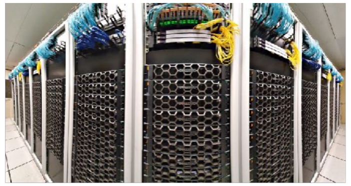
new GEM-based ROC









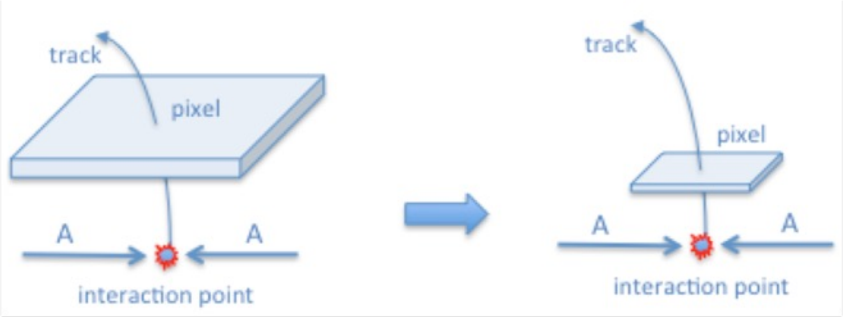


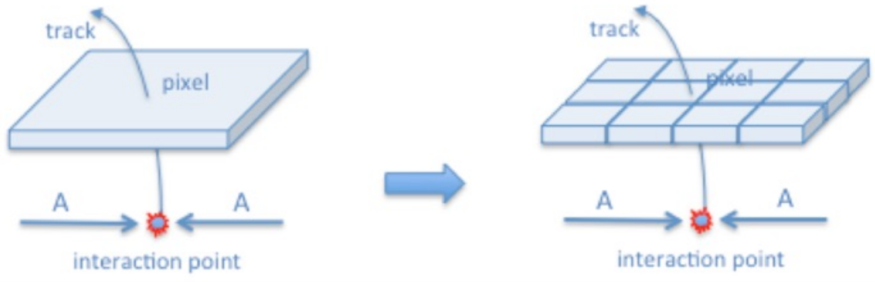
Integrated Online-Offline system (O^2)

Readout upgrade
TOF, TRD, MUON, ZDC, Calorimeters

ITS2 Design Objectives

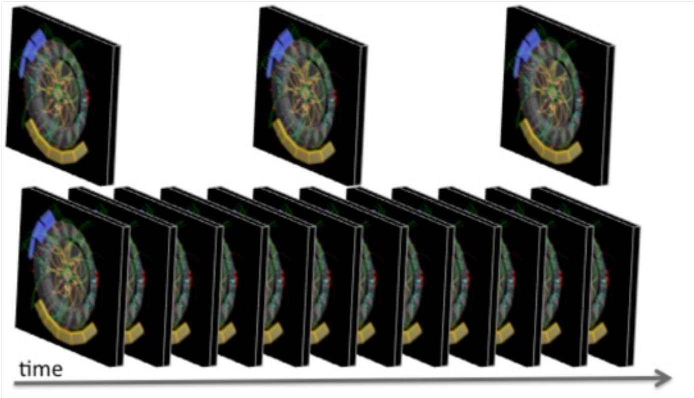
- Improve impact parameter resolution by factor ~3 in rϕ and factor ~5 in z at p_T = 500 MeV/c
  - Get closer to IP: 39 mm -> 23 mm
  - Reduce material budget: 1.14% X_0 -> 0.35% X_0 (inner layers)
  - Reduce pixel size: 50 x 425 μm² -> ~30 x 30 μm²





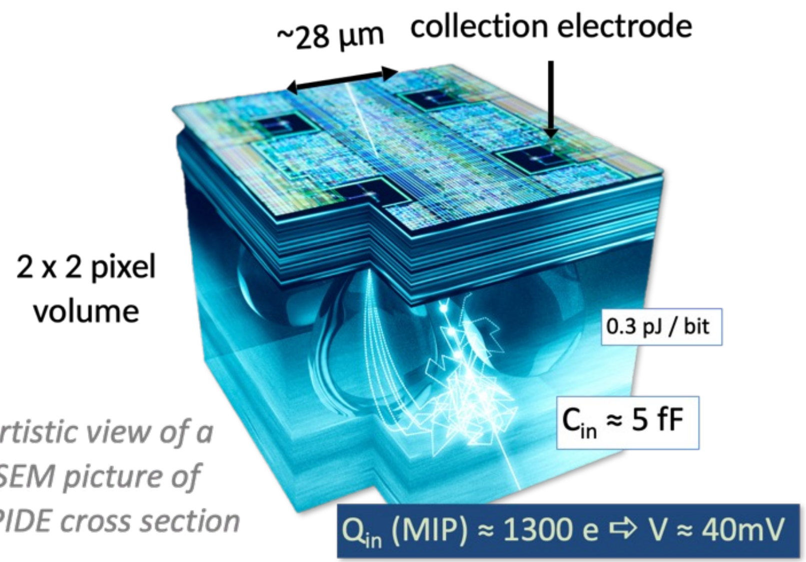
- Improve tracking efficiency and p_T resolution at low p_T
  - Increase number of track points: 6 -> 7 layers

- Fast readout
  - Readout of Pb-Pb collisions at 100 kHz (ITS1: 1 kHz) and p-p at 400 kHz

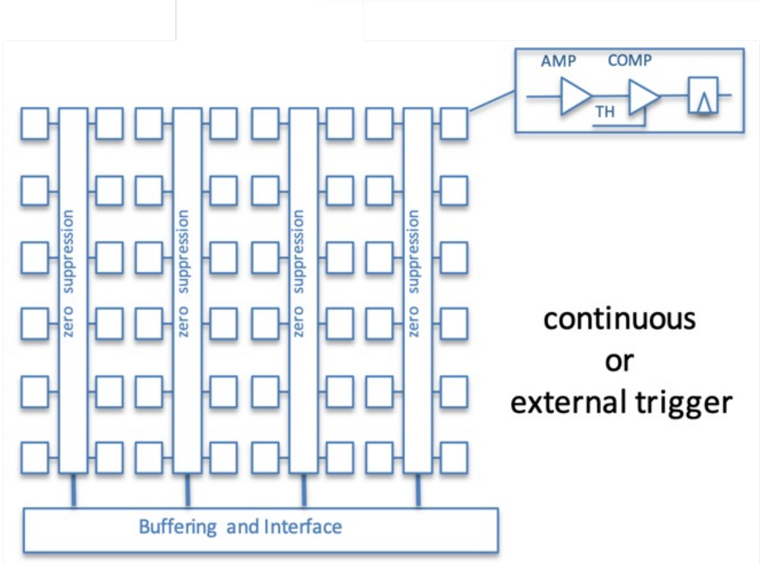


ITS TDR: J. Phys. G: Nucl. Part. Phys. 41 (2014) 087002

ITS2 pixel chip: ALPIDE



Artistic view of a SEM picture of ALPIDE cross section



CMOS Pixel Sensor – Tower Semiconductor 180nm CMOS Imaging Sensor (CIS) Process

ALPIDE Key Features

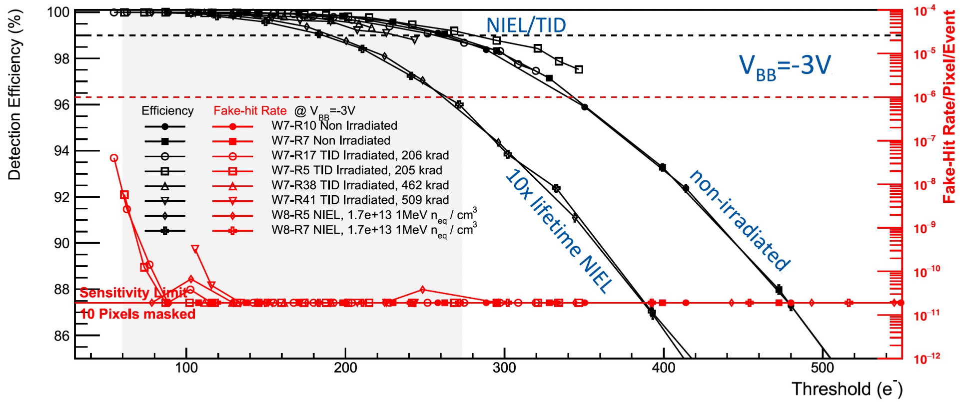
- In-pixel: Amplification, Discrimination, multi event buffer
- In-matrix zero suppression: priority encoding
- Ultra-low power < 40mW/cm^2 (< 140mW full chip)
- Detection efficiency > 99%

- Spatial resolution ~5µm

- Low fake-hit rate: << 10^{-6}/pixel/event (10^{-8}/pixel/event measured during commissioning)

- Radiation tolerance:
  - 270 krad total ionising dose (TID),
  - > 1.7 10^{13} 1MeV/n_{eq} non-ionising energy loss (NIEL)

- Same chip used for ITS and Muon Forward Tracker (MFT)



ALPIDE detection efficiency and fake hit rate

ALPIDE and other developments

ALICE

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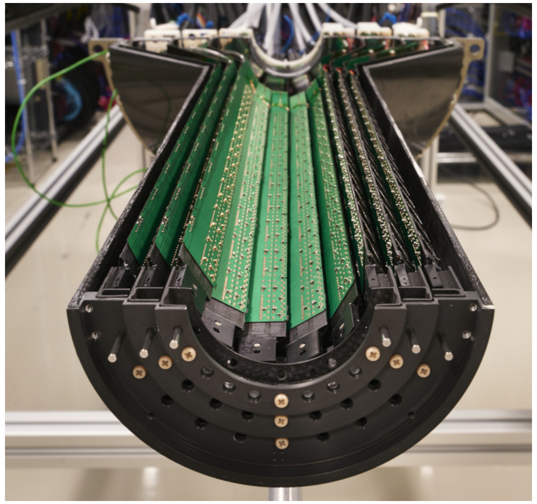
ALPIDE: Tower Semiconductor 180nm CMOS Imaging Sensor (CIS) Process

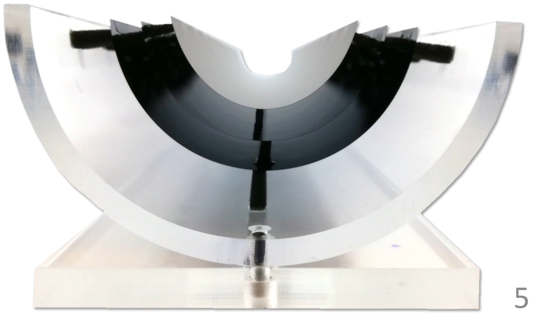
- R&D effort within the ALICE collaboration
  - excellent collaboration with foundry
  - more than 70k chips produced and tested
  - ALICE ITS pioneers large area trackers built of MAPS (ALICE 3)
- in parallel studies to optimise process to reach full depletion and improve time response and radiation hardness up to 10^{15} $1MeV/n_{eq}$:
  - **More details:** NIM **A871** (2017) https://doi.org/10.1016/j.nima.2017.07.046
  - **Now being further pursued: MALTA, CLICpix, FastPix, …**

ITS2 Inner Barrel



FUTURE: TPSCo 65 nm CMOS Imaging Sensor (CIS) Process

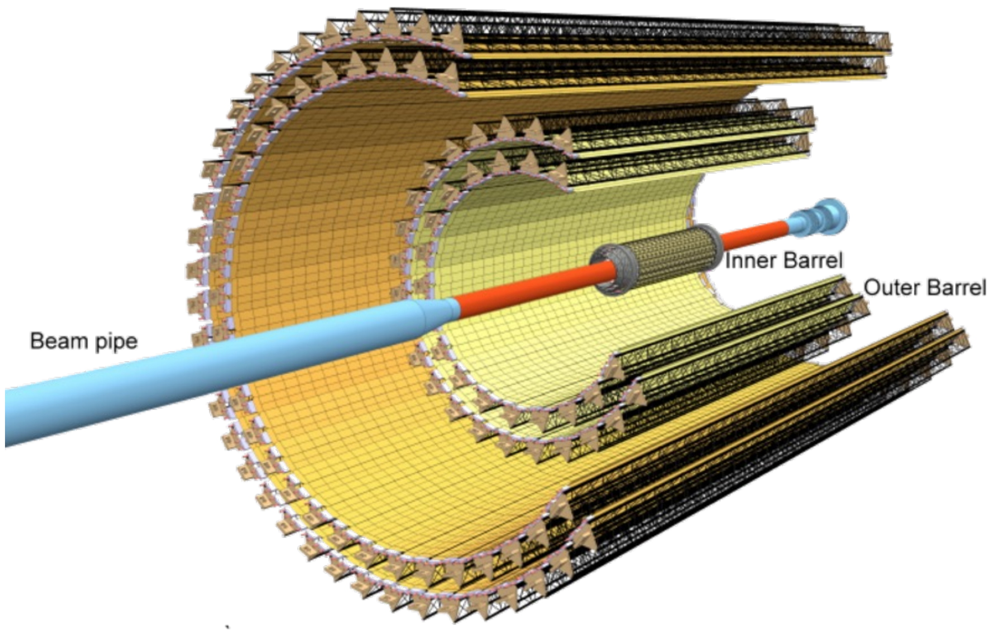
- **what next? ITS3: all silicon detector**
  - 2D stitching → large surface sensors
  - 300 mm wafers → 27×9 cm^2 sensor
  - single “chip” equips an ITS3 half-layer
  - thinned down to 20-40 µm
    -> flexible, bent to target radii

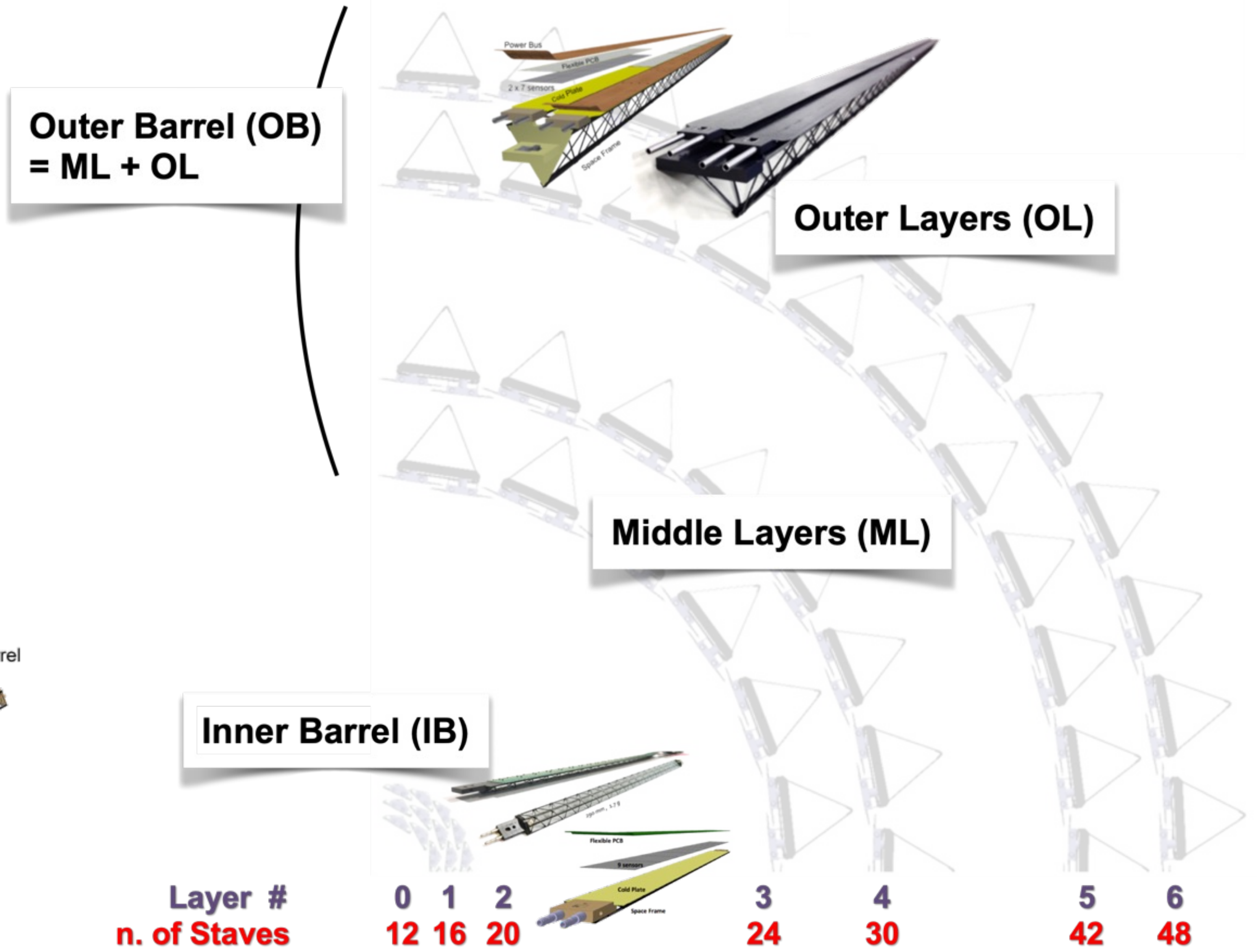


follow Laura Gonella’s talk this afternoon

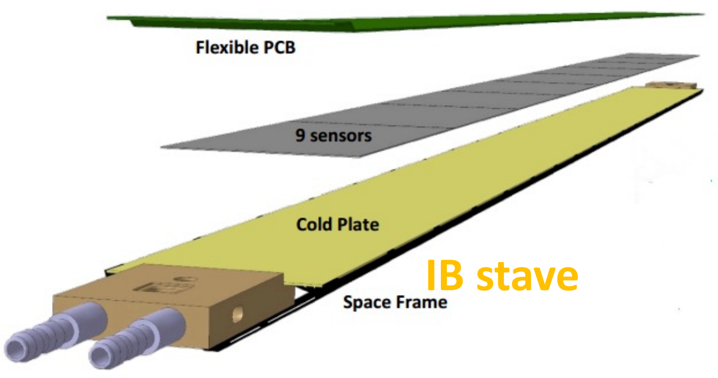
ITS2 Layout

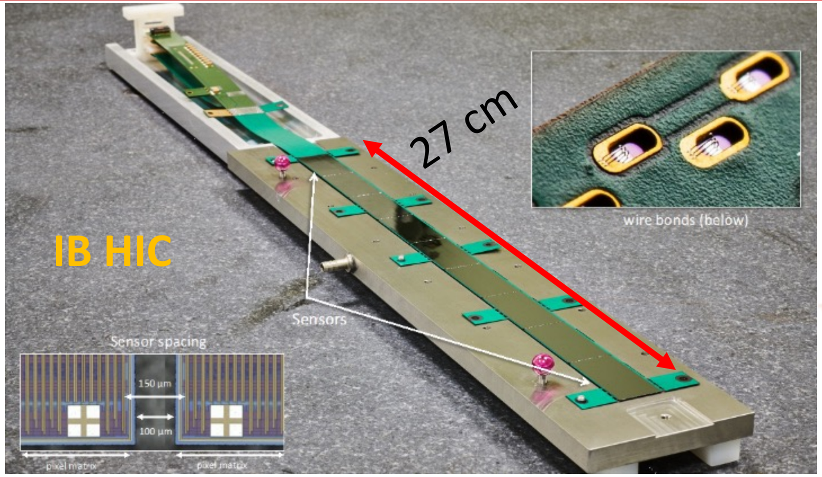
- 7 Layers (3 inner / 2 middle / 2 outer) from R = 22 mm to R = 400 mm
- 192 Staves (48 IL / 54 ML / 90 OL)
- Ultra-lightweight support structure and cooling
- 10 m^2 active silicon area, 12.5 x 10^9 pixels

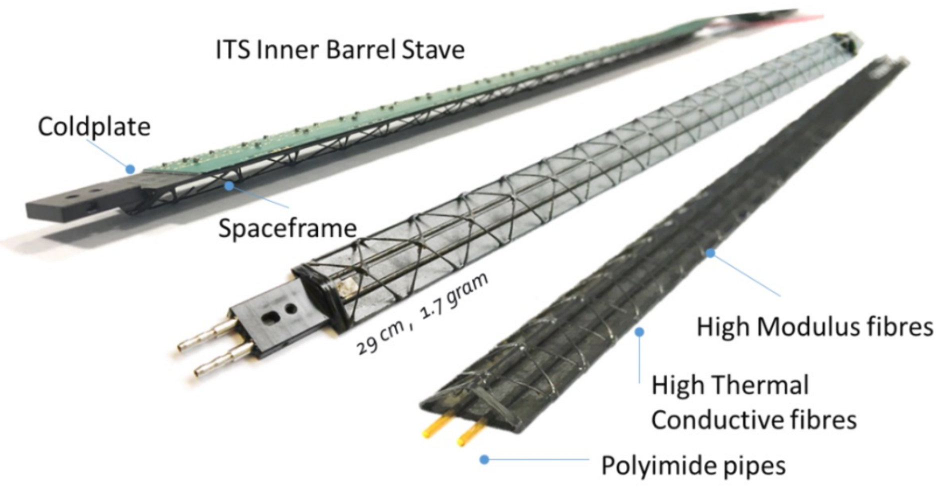




ITS2 Inner Barrel





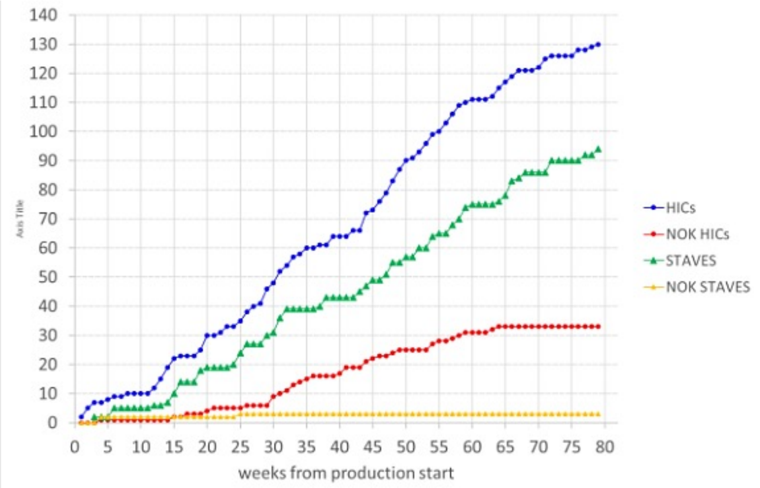


Inner Barrel (IB):

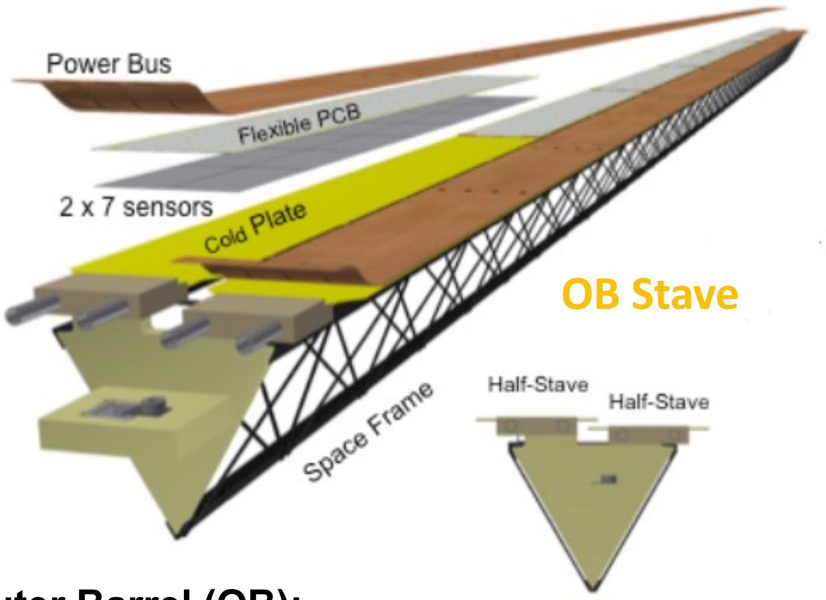
- Three layers
  - Layer0: 12 staves
  - Layer1: 16 staves
  - Layer2: 20 staves
- Hybrid Integrated Circuit (HIC): 9 sensors glued on Al Flexible Printed Circuit (FPC)
- Wirebonds electrically connect FPC to chips
- Stave: a HIC glued to cold plate and space frame
- Sensors read out separately

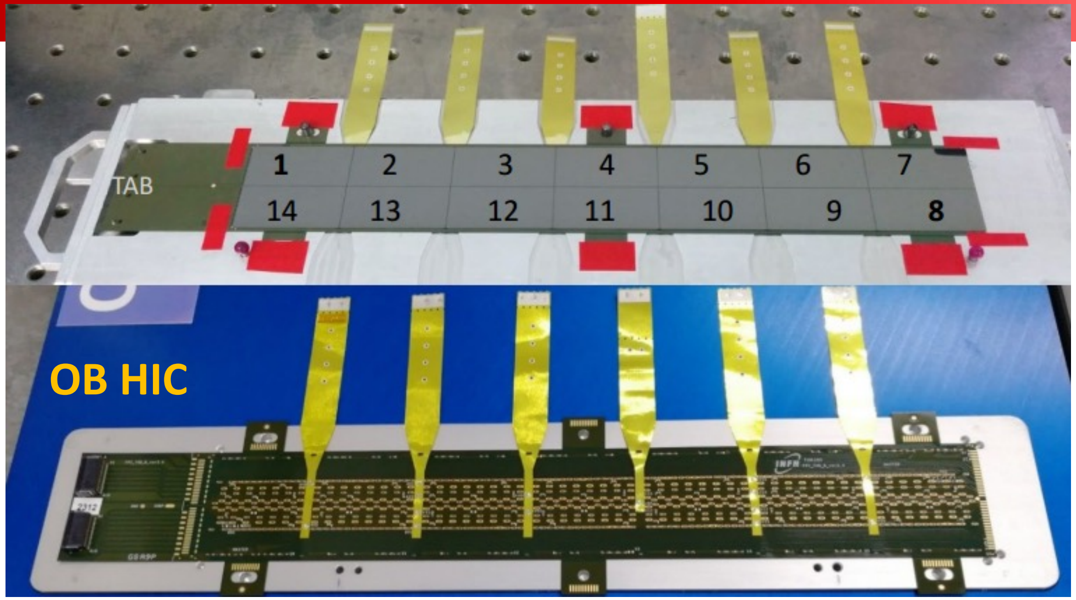
HIC & stave production:

- Production site: CERN
- 140 staves assembled
- Yield 73%
- **Production completed** and enough for two IB sets.



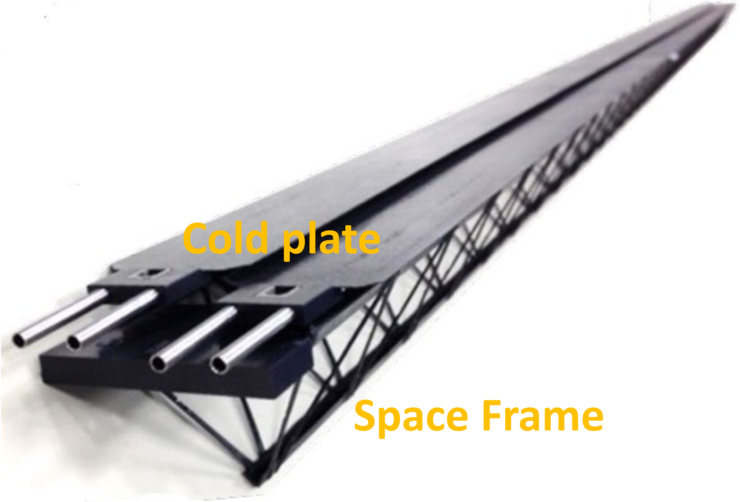
ITS2 Outer Barrel





Outer Barrel (OB):

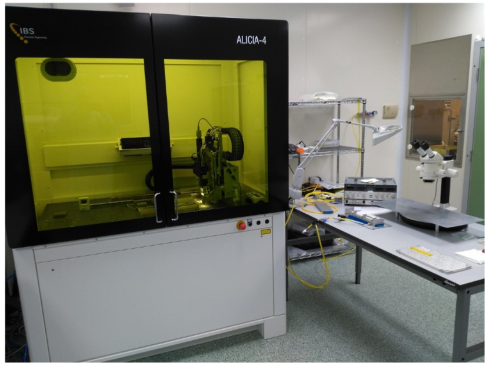
- OB HIC:
  - 7x2 sensors (2 rows) glued on Cu FPC
  - Wirebonds electrically connect FPC to chips
  - Power delivered via 6 cross-cables soldered to the FPC
  - Data and control are transferred through 1 master chip per row
- OB stave:
  - 4x2 HICs (for ML) or 7x2 HICs (for OL) glued to cold plate and space frame
- 54 ML staves (24 + 30) + 90 OL staves (42 + 48)

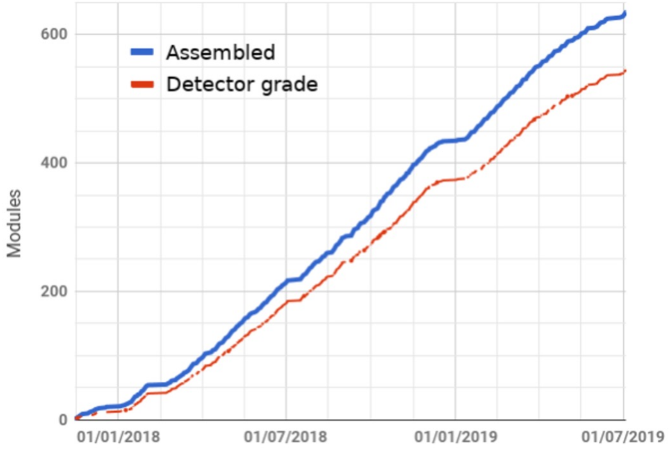


Outer Barrel Module Production Liverpool

M. Buckland, L. Boynton, A. Chadwick, M. Chartier, N. Clague, G. Contin, J. Iddon, S. Lindsay, M. Poblocki

- One of 5 sites: Bari (IT), Liverpool (UK), Pusan (KR), Strasbourg (FR), Wuhan (CN)
- Module Assembly Machine (MAM) designed and manufactured by collaboration for this purpose
- Assembly procedure:
  - Chips are aligned and glued to FPC
  - Wirebonding
  - Functional tests
  - Shipped to stave sites
- 635 modules produced
- Production completed July 2019
- Liverpool detector grade yield 85%
- Developed and carried out metrology procedures
- Developed short curing technique to make 1 more module a day, used by the all production sites

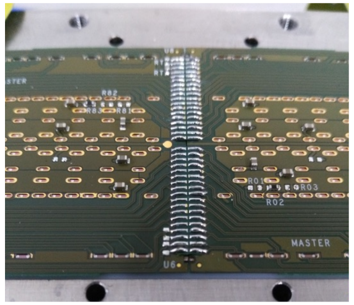


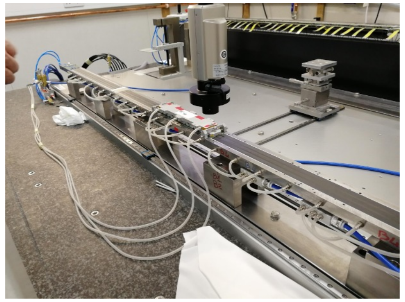


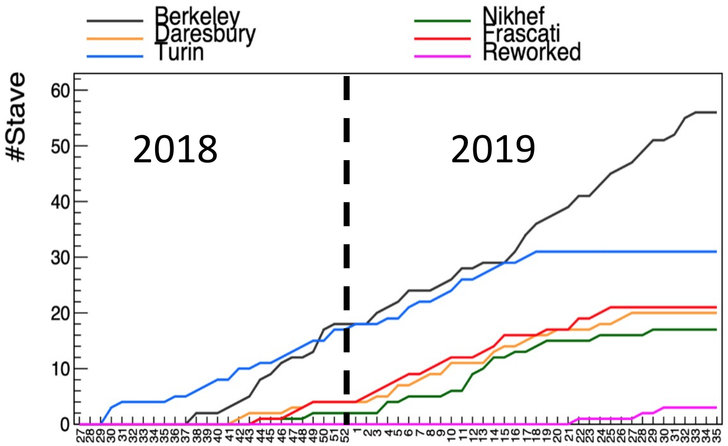
Outer Barrel Stave Production Daresbury

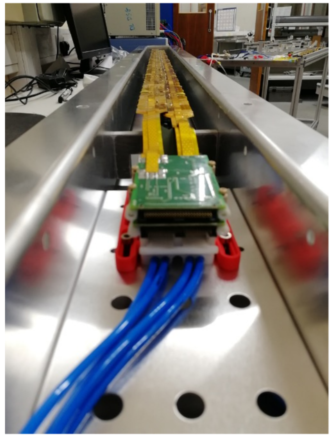
G. Markey, T. Lee, A. Hill, M. Borri, M. Buckland, N. Clague, G. Contin, J. Iddon, E. Latham-Taylor, R. Lemmon, J. Liu, M. Poblocki, P. Hindley, G. Morris

- Stave institutes: Berkeley (US), Daresbury (UK), Frascati (IT), Nikhef (NL), Turin (IT)
- Coordinate Measuring Machine (CMM) with 2m bed purchased for this purpose
- Assembly procedure:
  - Modules are aligned and glued to cold plate
  - Inter-module connection (soldering)
  - Functional tests
  - Aligned and glued onto space-frame
  - Power bus connection
  - Functional tests
  - Packed and shipped to CERN
- 22 staves assembled
- Stave detector grade yield in Daresbury is 95.5%



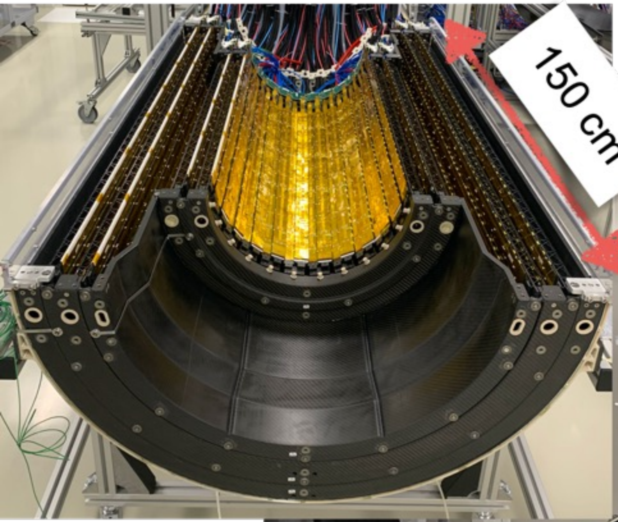




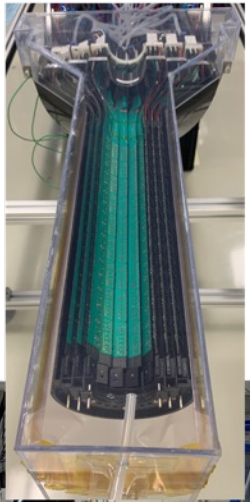


On-Surface Commissioning

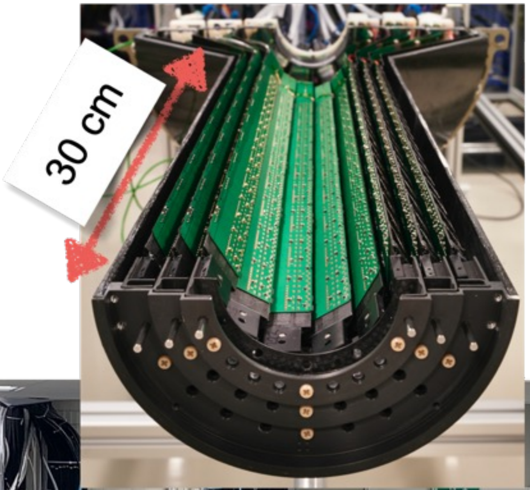
Outer Barrel Top



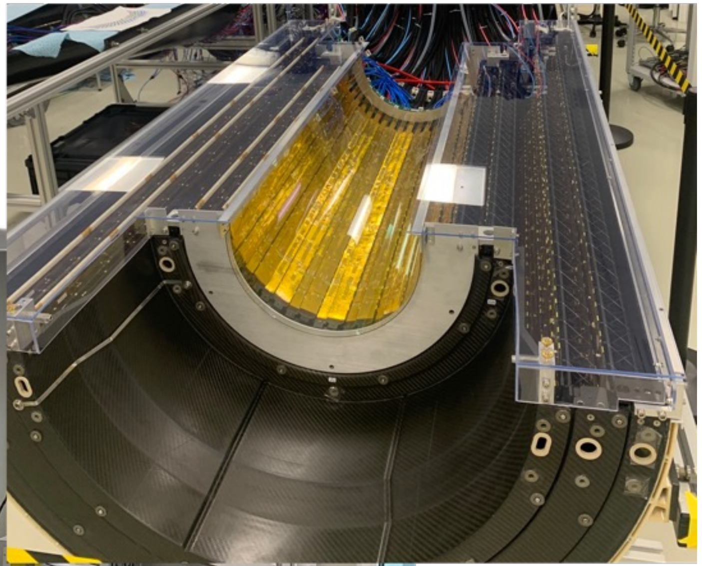
Inner Barrel Top



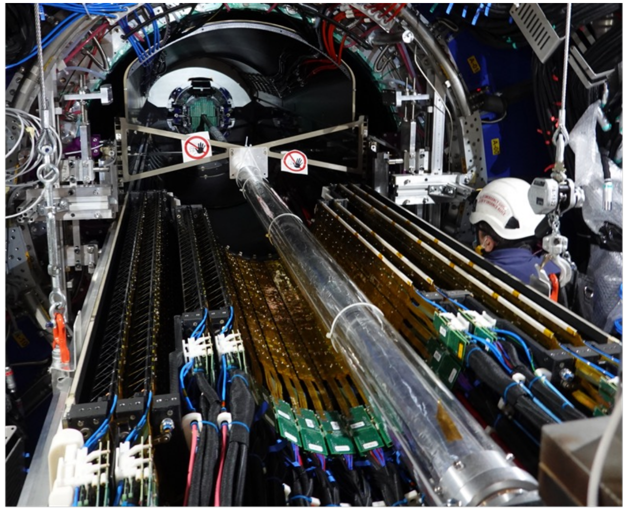
Inner Barrel Bottom



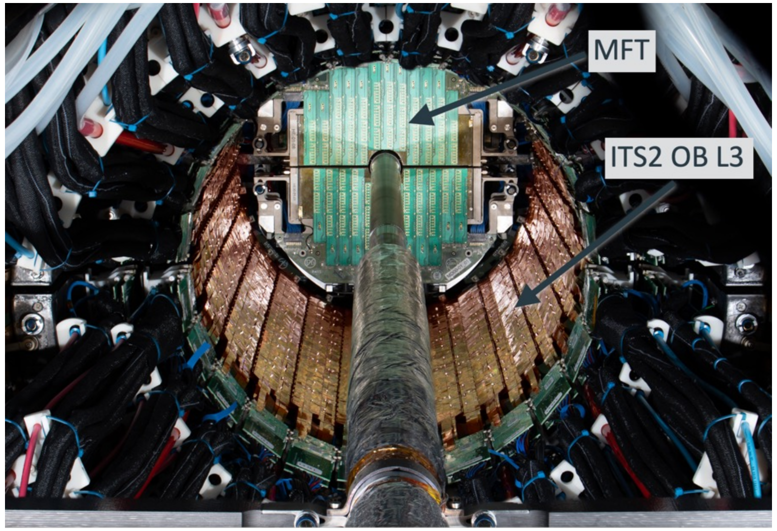
Outer Barrel Bottom



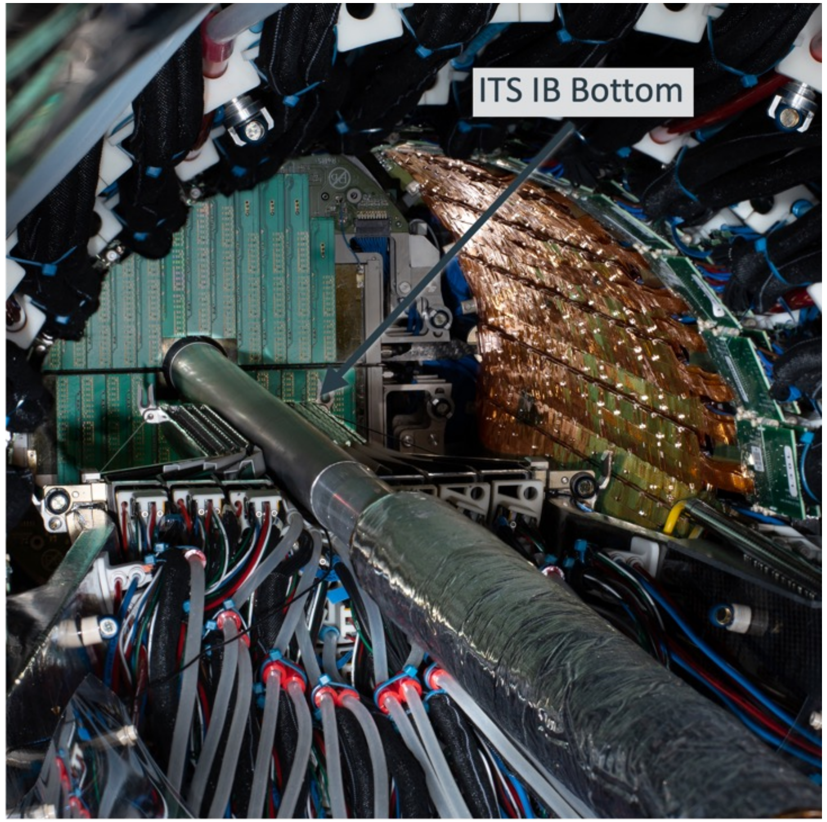
ITS installation



Outer Barrel Bottom being inserted on the rails inside the TPC



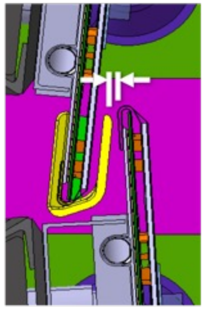
ITS Outer Barrel surrounding the beam pipe, MFT in the back



ITS Inner Barrel Bottom and Outer Barrel

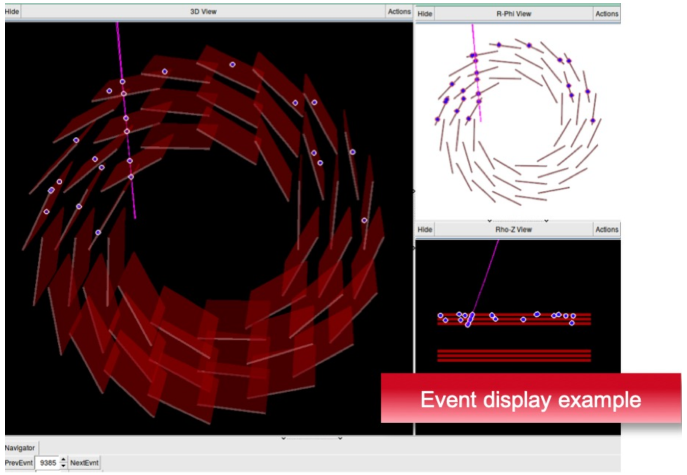
- Installation challenges
  - Precise positioning around the beam pipe (nominal clearance ~ 2 mm)
  - Manipulating from 4 m distance
  - Difficult to see actual position by eye
  - precise mating of top and bottom barrel halves (clearance between adjacent staves ~ 1.2 mm)
- Dry-installation tests on the surface to test and exercise procedures
- Use of 3D scans, surveys and cameras

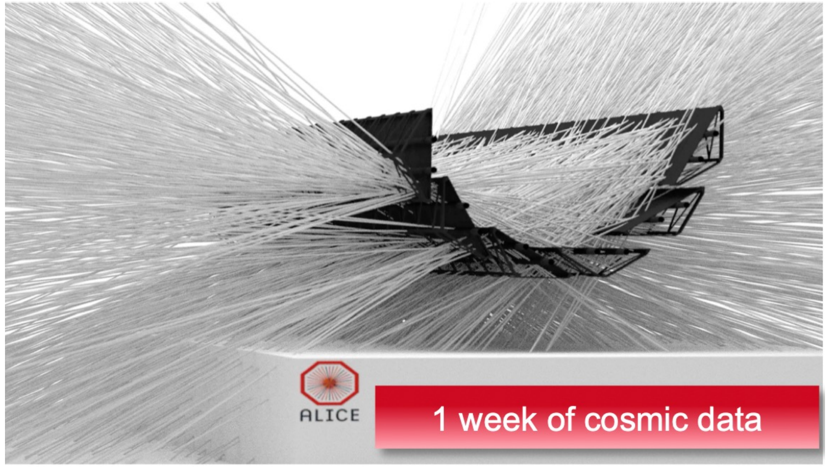
1.2 mm nominal clearance

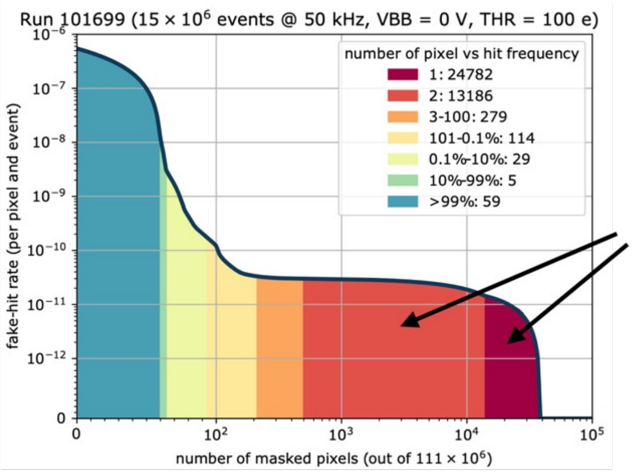


OB stave edge clearance when fully mated

On-Surface Commissioning results



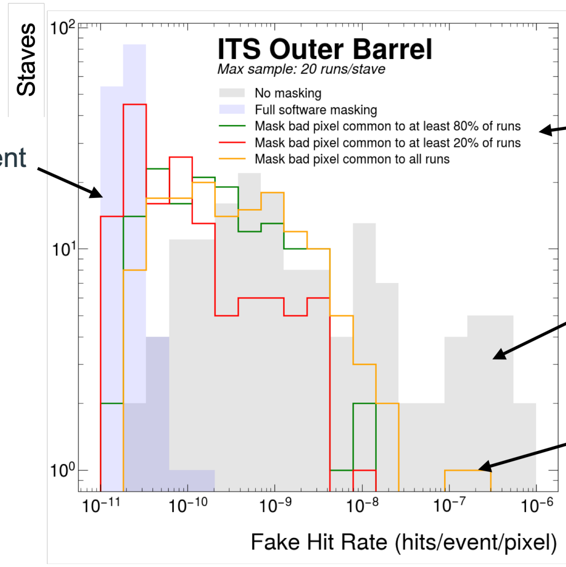




Hits from cosmic muons

- Cosmics tracks reconstructed
- IB: fake-hit rate of 10^{-10} / pixel / event
  - Achieved by masking fraction of 10^{-8} pixels
- OB: fake-hit rate of 10^{-8} / pixel / event
  - Achieved by masking noisy pixels common to all runs
- Bit-error-free data transmission for several tens of hours at nominal operating conditions
  - Large operational margin in terms of occupancy and readout rate
  - Regular errors for extreme combinations of occupancy and trigger rate lead to negligible inefficiency (~1/s for full IB)

Offline masking: FHR 10^{-10} / pixel / event



Requirement: 10^{-6} / pixel /event

Exclusion of broken double-columns

Masking noisy pixels common to all runs → realistic estimate for hardware masking

Excellent Fake-Hit Rate (FHR) in the entire OB

Calibration

The Challenge:

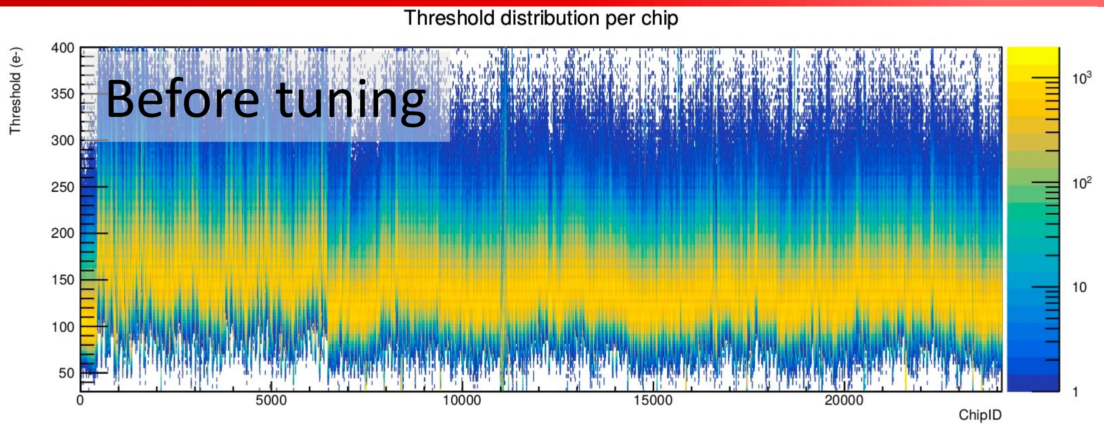
- Online calibration of 12.5 billion channels
- Threshold scan of full detector: > 50 TB of event data
- Several scans to be run sequentially
    - Threshold tuning (adjust thresholds to target)
    - Threshold scan (measure actual thresholds)

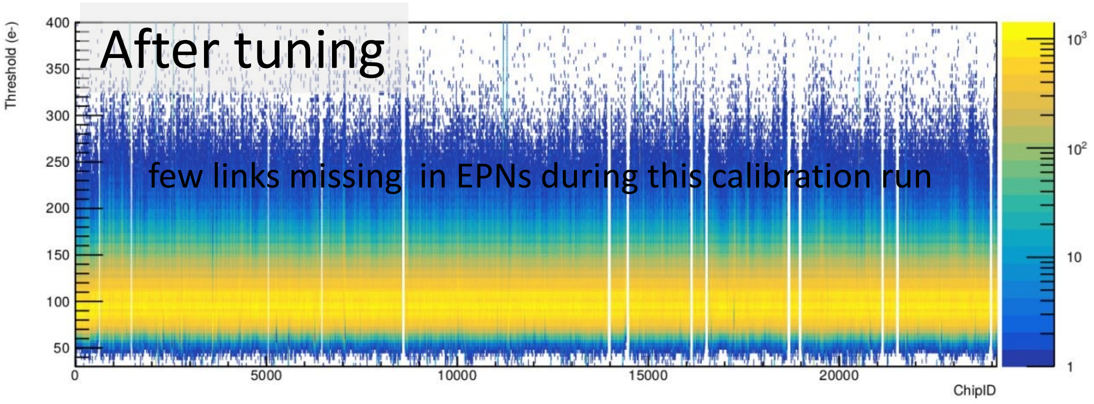
Procedure:

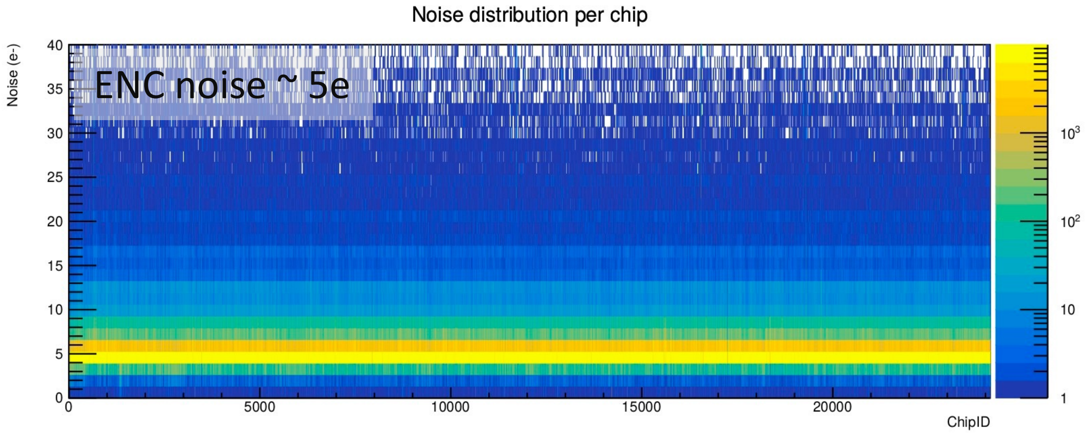
- DCS performs actual scans: configure and trigger test injections
- Scan runs in parallel but independently on all staves
- Distributed analysis on event processing nodes
- full procedure takes **less than 30 minutes**

Results:

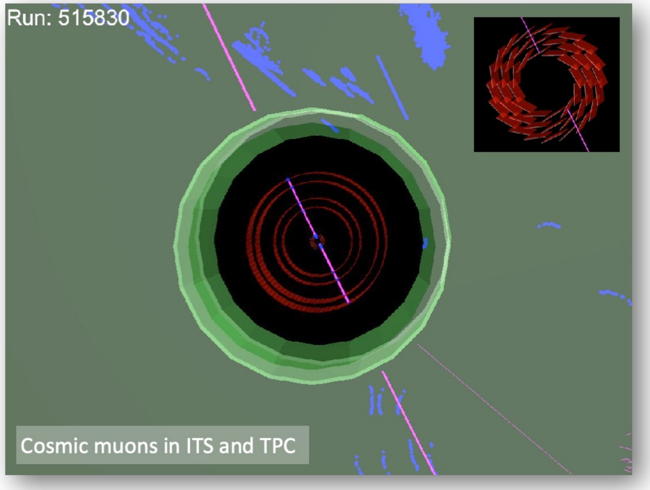
- Scan with online analysis successfully run on full detector
- before tuning: settings used in surface commissioning: detector already fully efficient
- After tuning:
    - Thresholds very stable on all the chips: RMS of threshold distribution per chip <23 e^- (compatible with what we had during production)
- ENC noise ~ $5e^-$

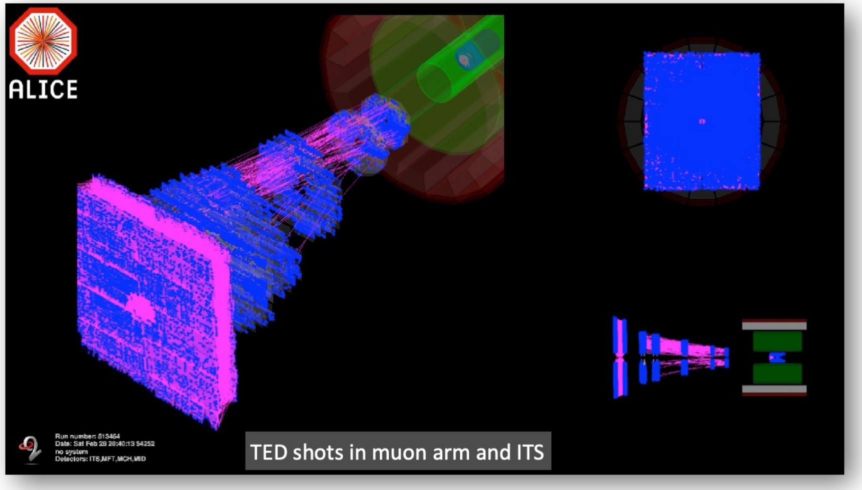


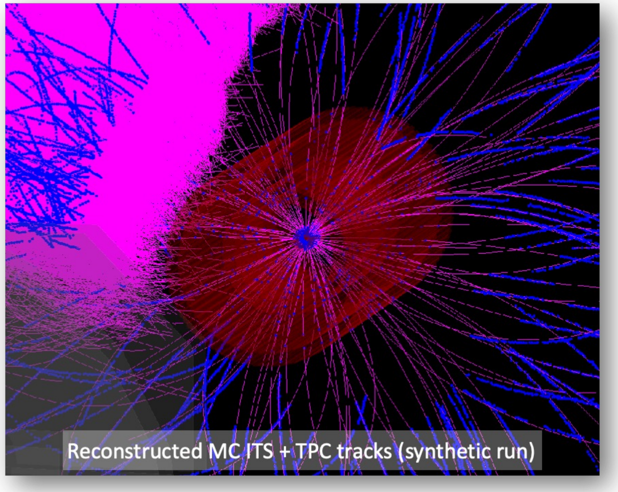


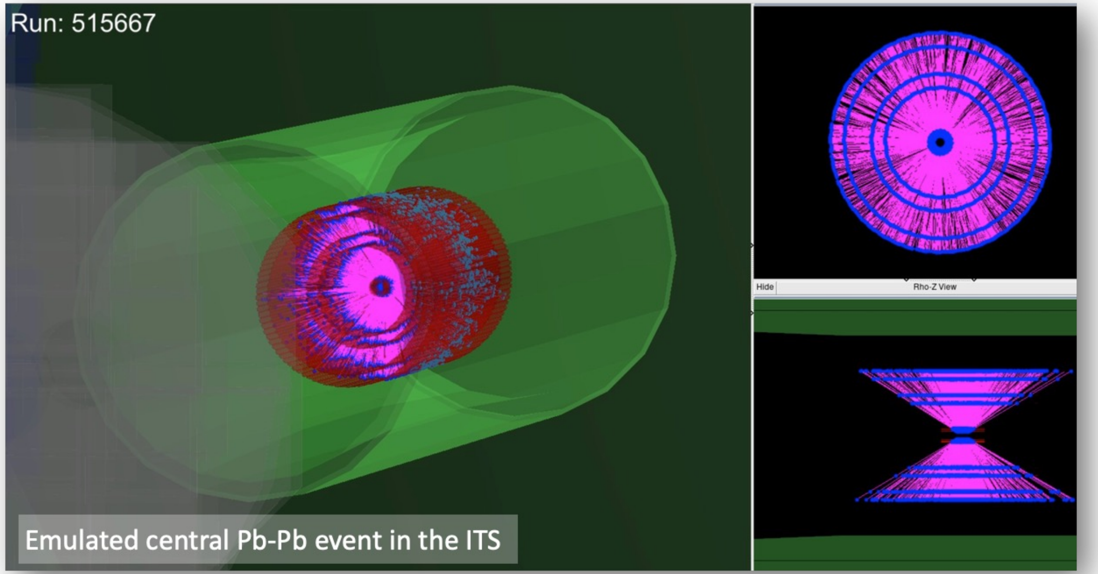


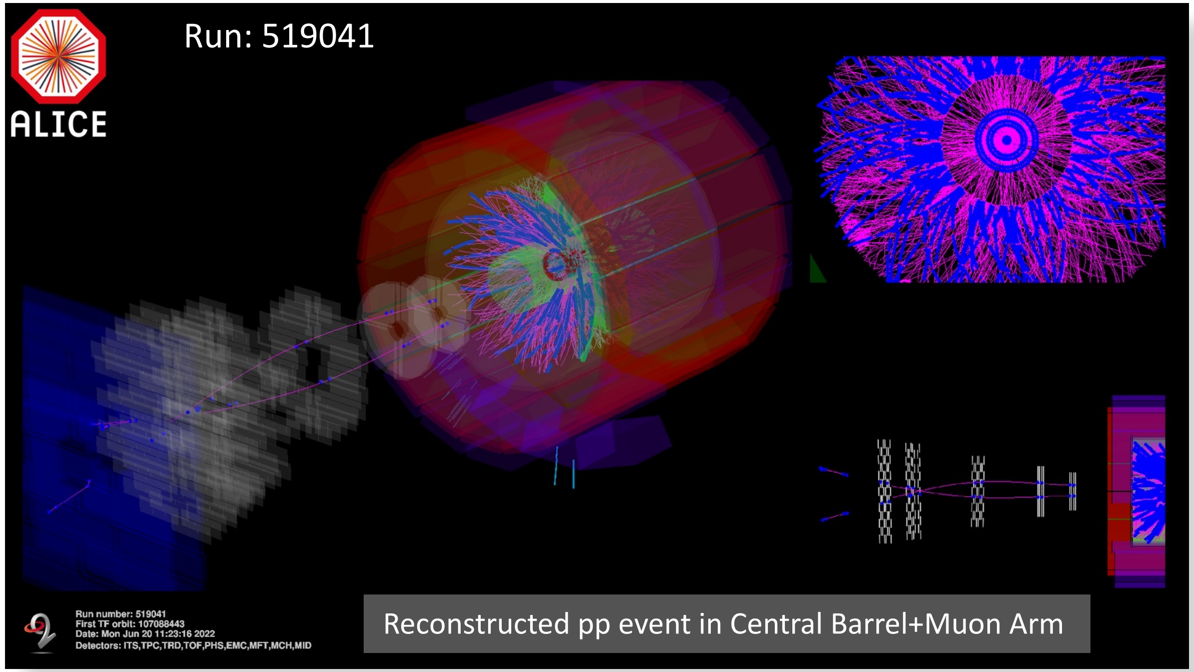
RUN 3 readiness





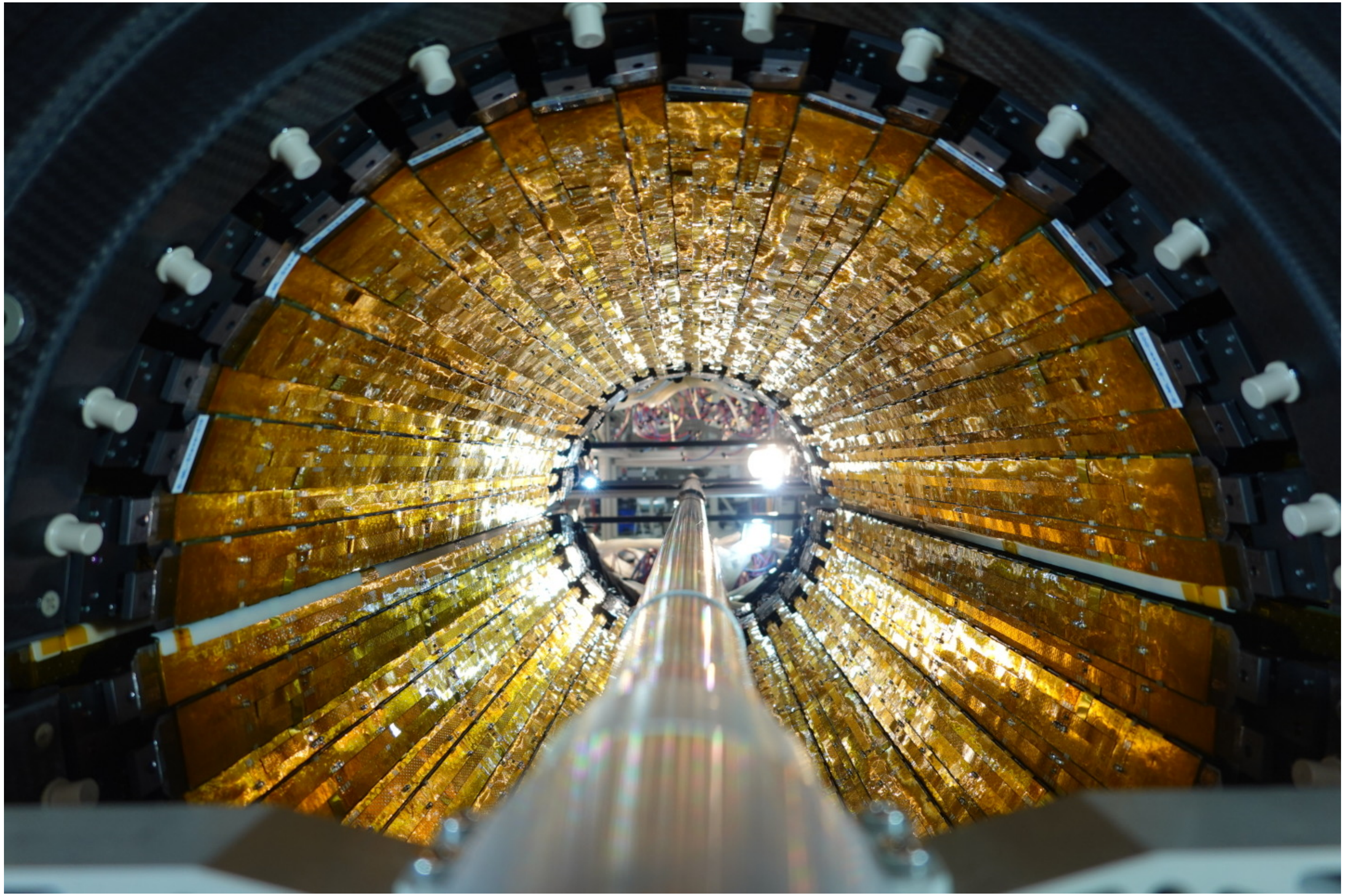






Conclusions

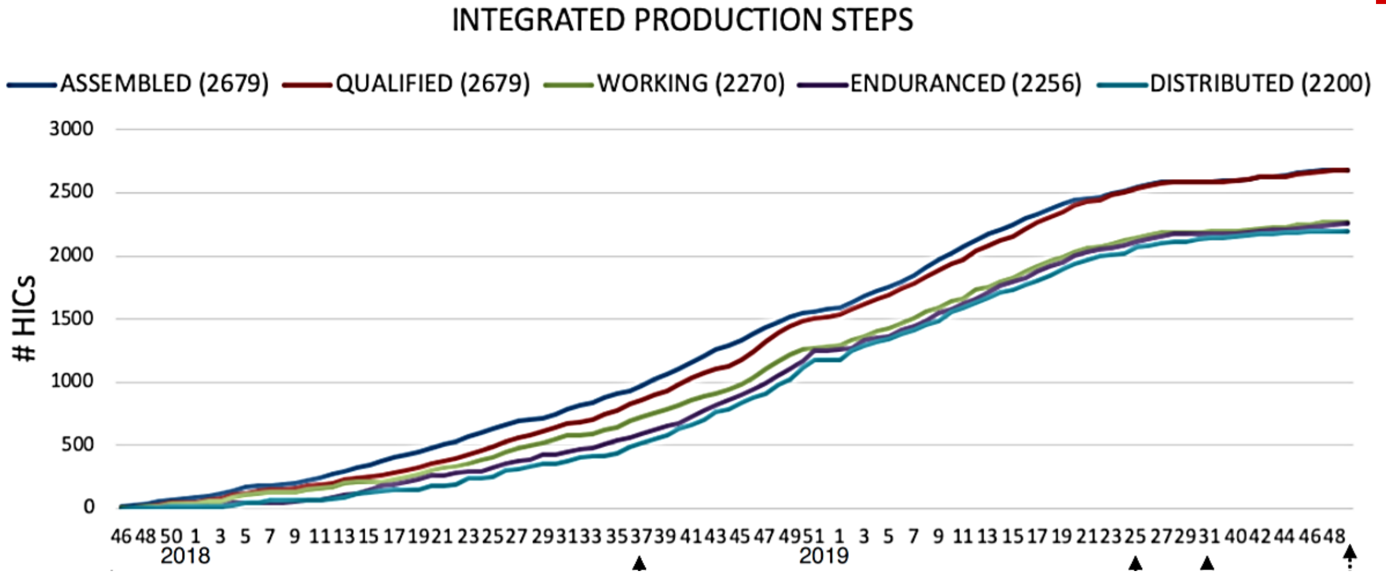
- ITS2 successfully installed and commissioned for LHC RUN3
- Calibration procedure established and tested
- DCS and QC tools ready for data taking
- Detector settings optimized both for pp and PbPb collisions
- RUN3 has already started this month with pp collisions and ITS2 detector has already taken data at 1MHz collision rate

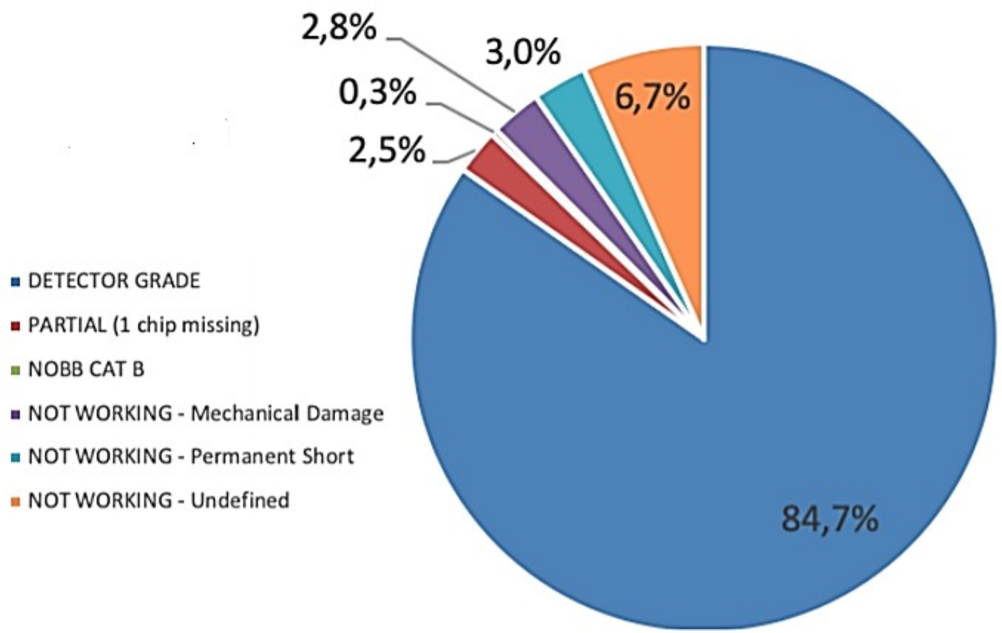


ALICE ITS2 Outer Barrel during insertion tests

BACK UP SLIDES

ITS2 OB HIC Production Summary





OB HIC production:

- HIC assembly sites: Bari, Liverpool, Pusan/Inha, Strasbourg, Wuhan
- FPC test and preparation sites: Trieste, Catania
- 1692 working HICs needed to build 90 OB staves
- 2679 HICs assembled and 2270 HICs qualified as Detector Grade (DG)
- 2200 HICs distributed to OB stave production sites

OB HIC YIELD

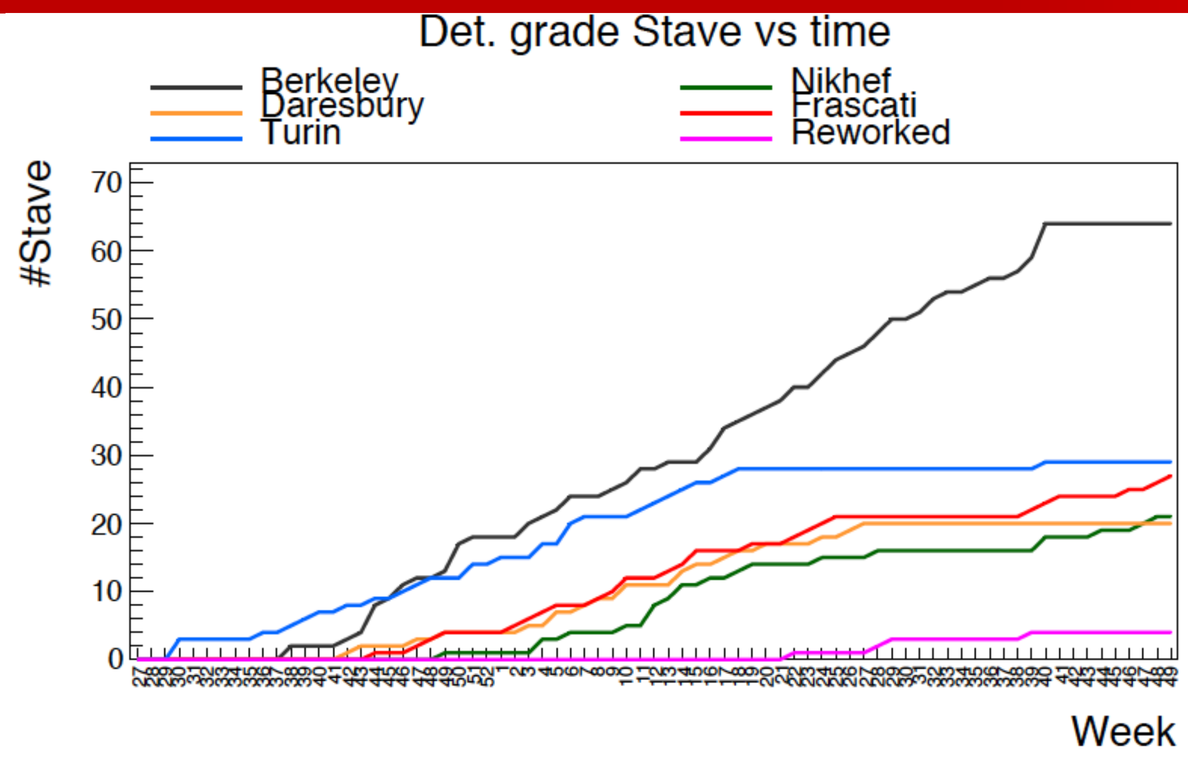
Gold/Silver + Bronze + Burnt through + NO Backbias

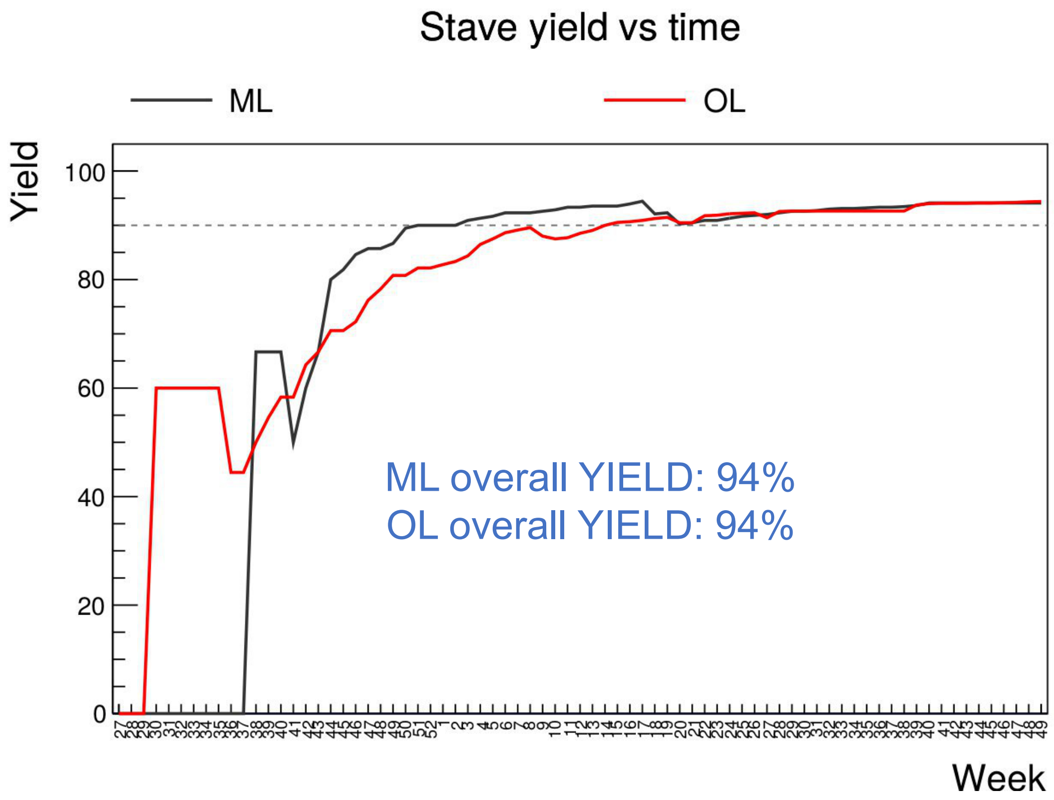
58.7%+11.1%+5.5%+9.4%

84.7%

Production completed on 25/11/2019

ITS2 OB Stave Production Summary





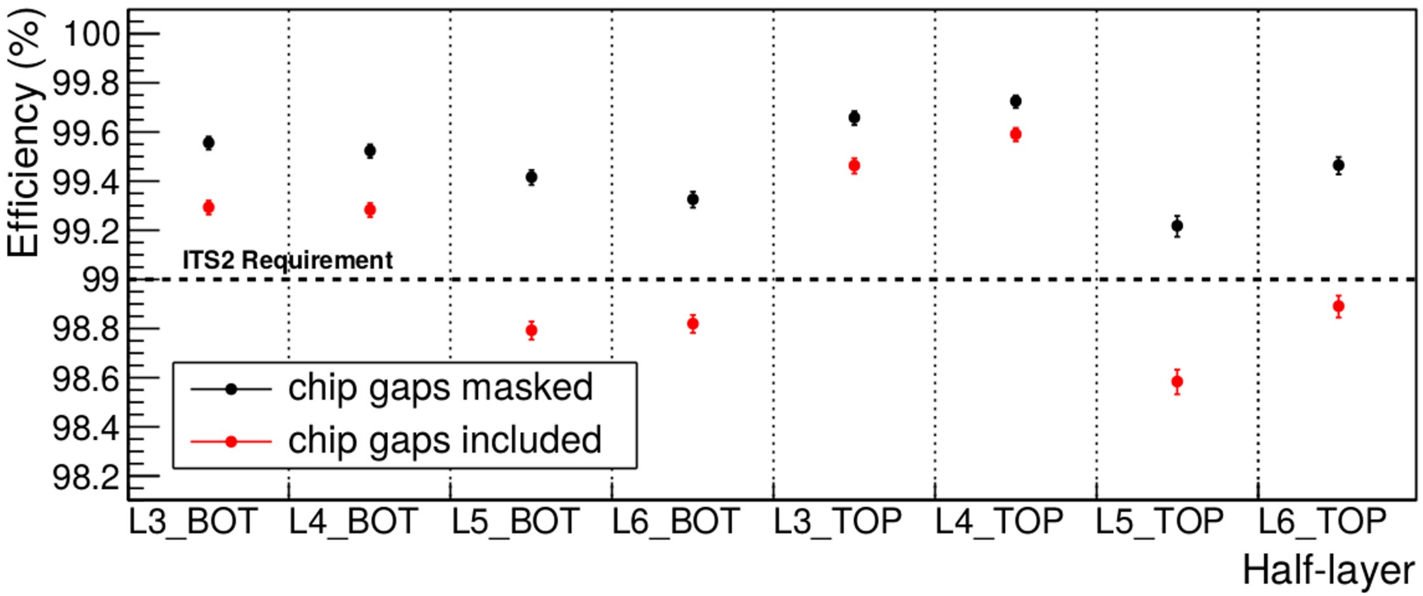
OB stave production:

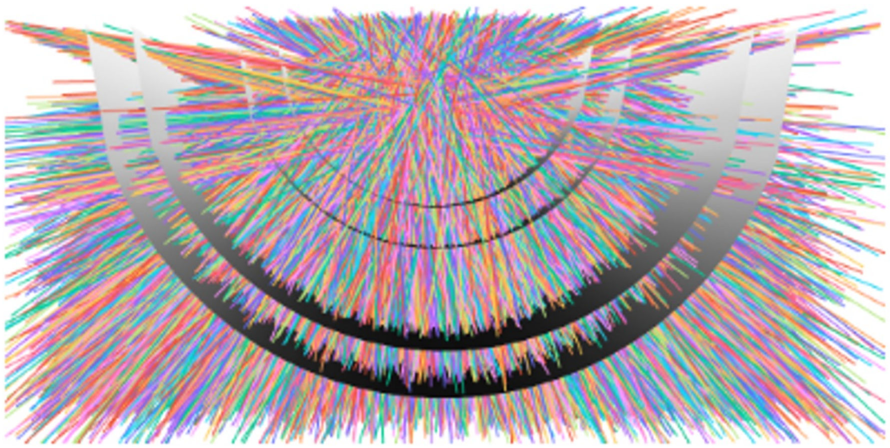
- production sites: Torino, Frascati, Daresbury and Nikhef (for OL), Berkeley (for ML)
- 68 (64 DG) ML staves + 107 (101 DG, including 4 reworked) OL staves assembled

ML production completed in October/2019
OL production completed in December/2019

On-Surface Commissioning – Outer Barrel Efficiency

- [Preliminary study] Efficiency of OB using cosmic tracks



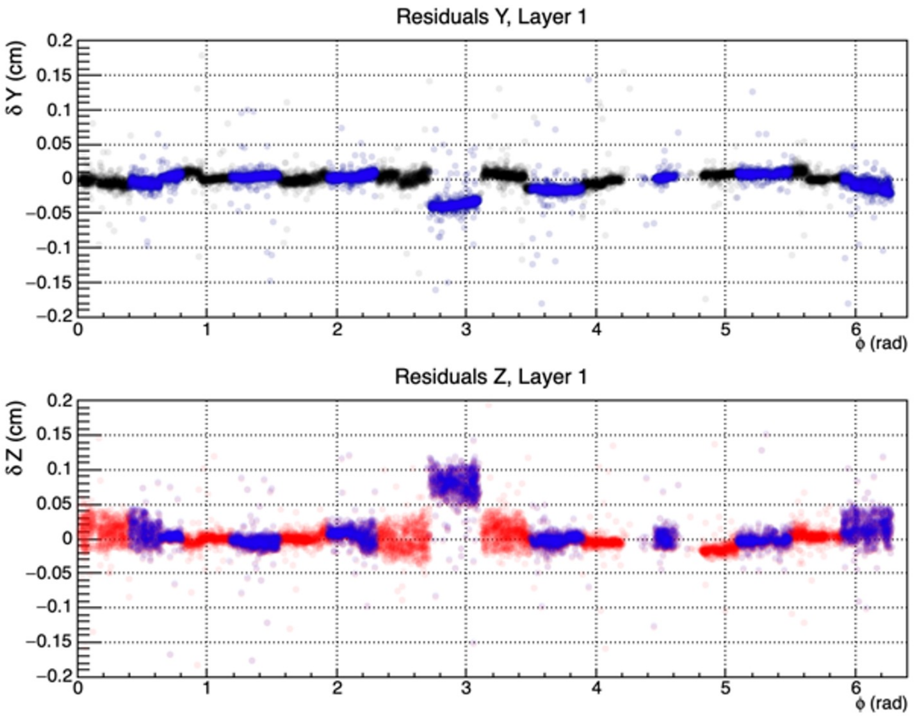


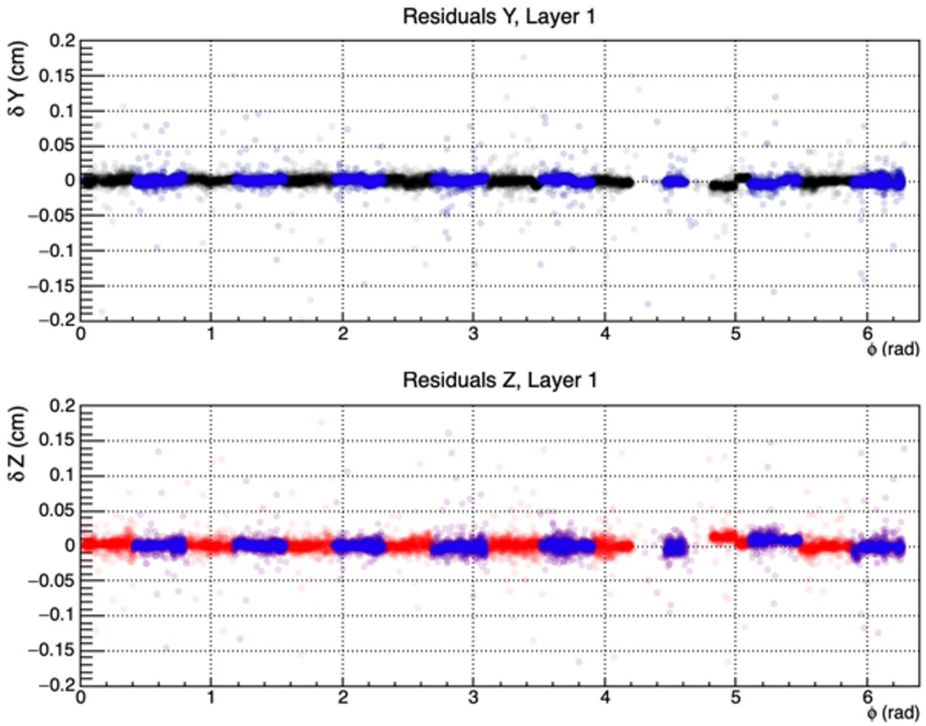
- Restricted to cosmic tracks passing through 10 cm sphere around interaction point for realistic track geometry
- Preliminary cut on chip gaps to restrict region-of-interest to sensitive area
- Measured efficiency well above 99% for all layers

Data Preparation: alignment

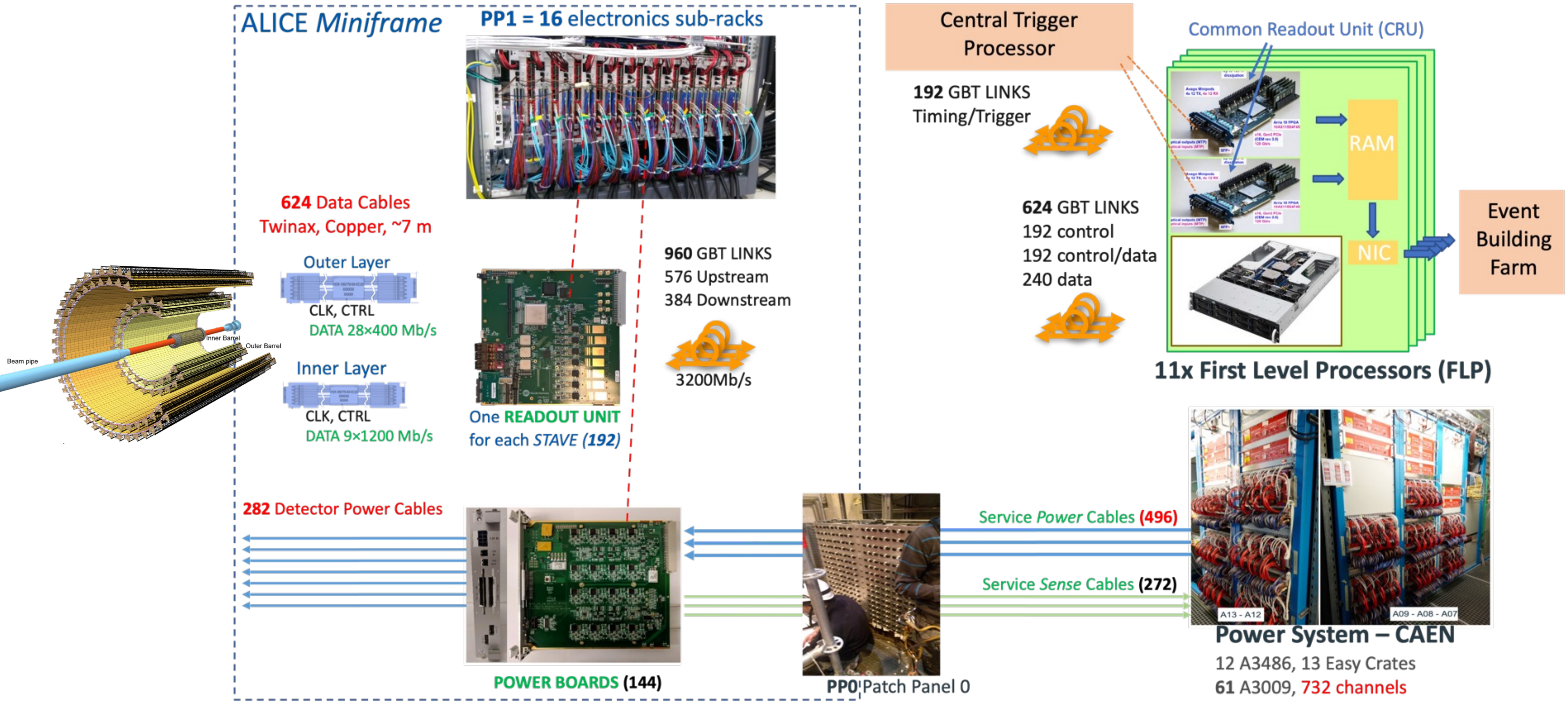
- Manual pre-alignment concluded with precision of O(100 μm)
- Ongoing: pre-alignment in R, Rf and Z using Millepede
  - currently at O(10 μm) for Inner Barrel and O(50μm) for Outer Barrel)
- Next step: fine alignment targeting a precision of a few μm (using Millipede, or AI approaches)

Below: example, Y and Z residuals in L1, before and after alignment with Millepede





Power and Readout System Overview



Collision systems	pp, pPb, Pb-Pb	pp, pPb, Xe-Xe, Pb-Pb	pp, pO, OO, pPb, Pb-Pb	pp, pPb, Pb-Pb	pp, pA?, AA	pp, pA?, AA
LHC schedule	RUN 1 2009-2013	RUN 2 2015-2018	RUN 3 2022-2025	RUN 4 2029-2032	RUN 5	RUN 6

High luminosity for ions (~$7 \cdot 10^{27}$ cm^{-2} s^{-1})

HL-LHC (~$5\text{-}7.5 \cdot 10^{34}$ cm^{-2} s^{-1})

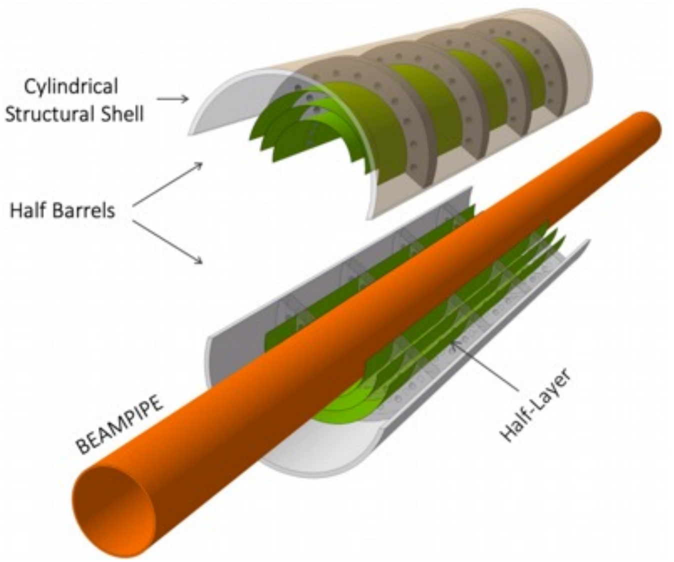
Higher luminosities for ions

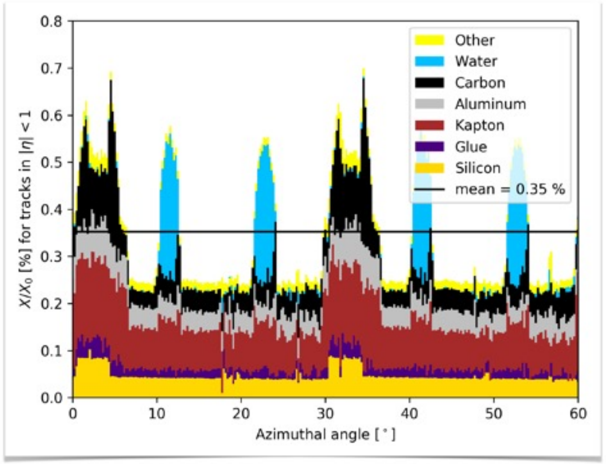
ATLAS	ATLAS	ATLAS phase I upgrade	ATLAS phase II upgrades	
CMS	CMS	CMS phase I upgrade	CMS phase II upgrades	
LHCb	LHCb	LHCb upgrade I(a)	LHCb upgrade I(b)	LHCb upgrade II
ALICE	ALICE 1	ALICE 2 upgrade	ALICE 2.1 upgrade	ALICE 3 upgrade

intermediate upgrade

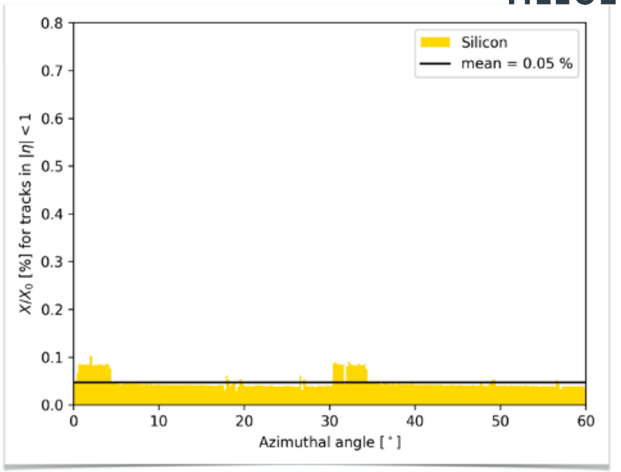
major upgrade

ALICE 2.1: ITS3 all silicon detector



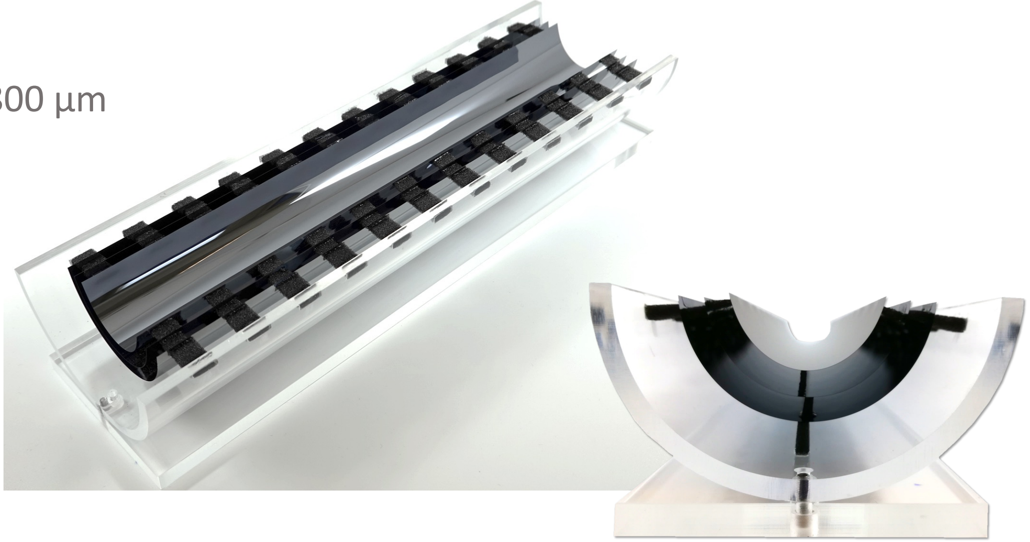


ITS2 Layer 0: X/X0=0.35



ITS3 only silicon: X/X0=0.05

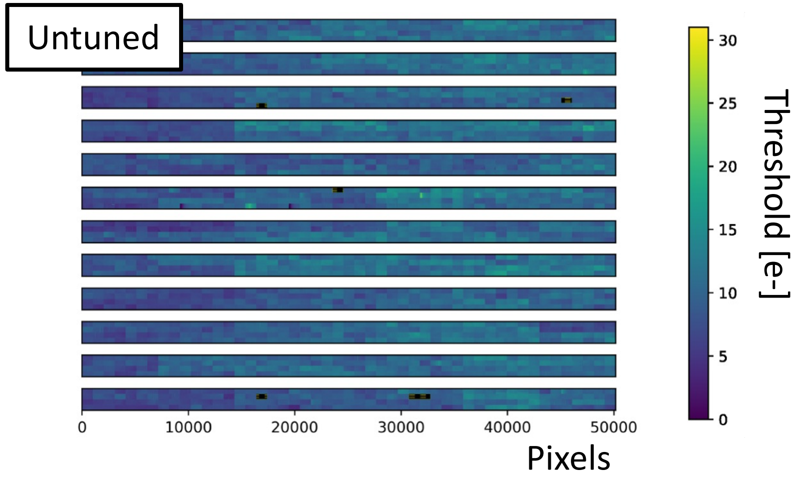
- Goal: improve vertexing at high rate
- Layout: 3 layers, replace ITS Inner Barrel,
  - beam pipe: smaller inner radius (18.2 mm to 16 mm) and reduced thickness (800 µm to 500 µm)
  - innermost layer: mounted around the beam pipe, radius 18mm (was 22 mm)
- Technology choices:
  - 65 nm CIS of Tower & Partners Semiconductor (TPSCo):
    - larger wafers: 300 mm instead of 200 mm,
    - single "chip" equips an ITS3 half-layer (through stitching technology)
    - 6 sensors in total
  - thinned down to 20-40 µm
    - -> flexible
    - bent to target radii
  - mechanically held by carbon foam ribs with low density and high thermal conductivity



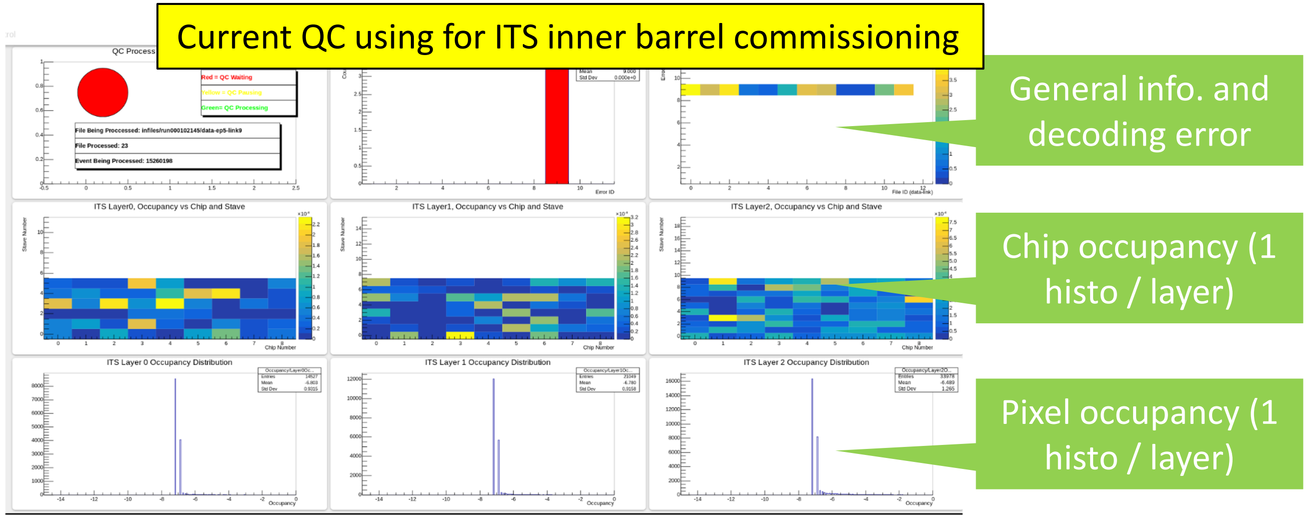
Letter of Intent for an ALICE ITS Upgrade in LS3 https://cds.cern.ch/record/2703140

ITS2 Commissioning Work by UK

- Production readout system
  - Developing readout software
  - Writing code for threshold scans on multiple staves (half barrel)
  - Determine the threshold of the pixels then tune for uniformity

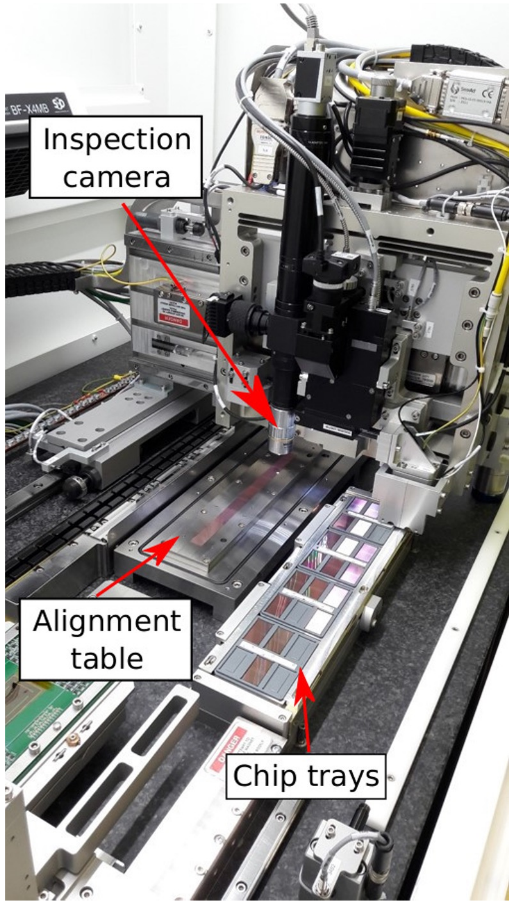


- Data Quality Control (QC)
  - Contribute to software development
  - Optimised QC is running
  - Trying to extract noisy pixel addresses through QC results
  - QC parallelization is under development to speed up processing time
  - Moving from inner barrel to outer barrel



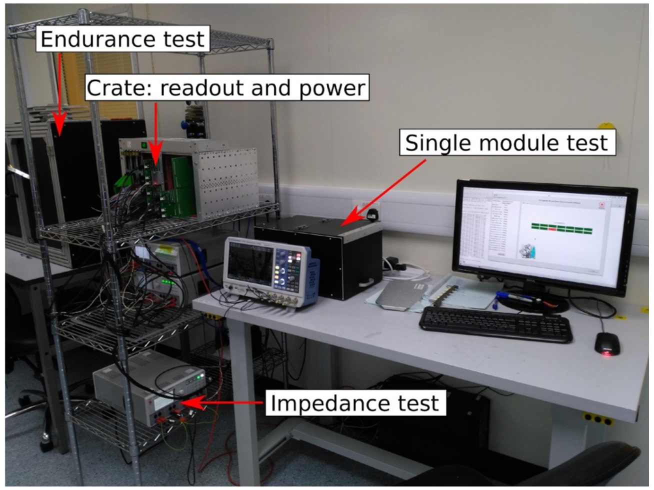
Outer Barrel Module Production Liverpool

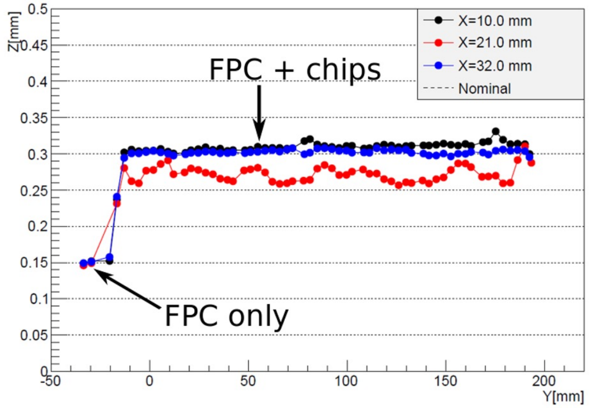
- Custom designed machine by IBS (NL) built to the project specifications
- So-called Module Assembly Machine (MAM):
  - Automatic chip pick up and placement
  - < 5 μm alignment precision
  - Automatic chip inspection
- Wirebonding on site



Outer Barrel Module Production Liverpool

- Extensive functional and mechanical testing for Quality Assurance (QA)
- Functional QA:
  - Impedance test, identify shorts
  - Single module, set of scans (e.g. threshold, nosie) to determine functionality of the readout, analogue and digital circuitry
  - Endurance test to determine the stability of the module over the expected number of power cycles during the detector operation
- Mechanical QA:
  - Pull tests on wirebonds to determine quality, 1 in 10 modules tested
  - Metrology: developed and carried out by Liverpool, determine mechanical properties and quality of assembly





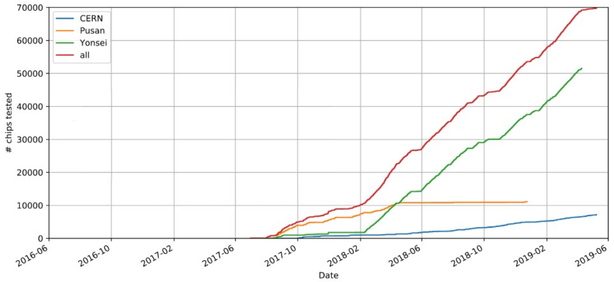
Thickness + flatness metrology

Component Production Status

ALPIDE chips

Production completed

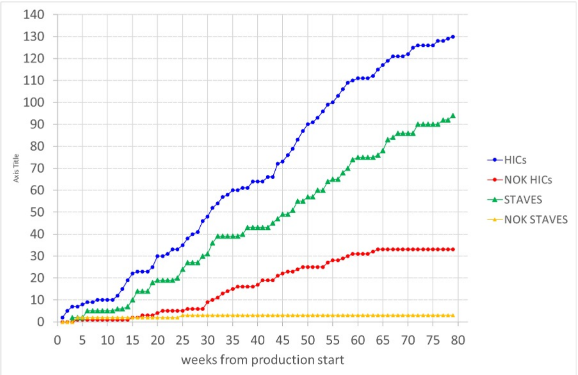
- Institutes: 50 µm: CERN, 100 µm: Yonsei, Pusan
- Total chips tested ~70000
- Total wafers ~1700
- Yield 64%
- Series test ended mid 2019



Inner barrel HICs and staves

Production completed

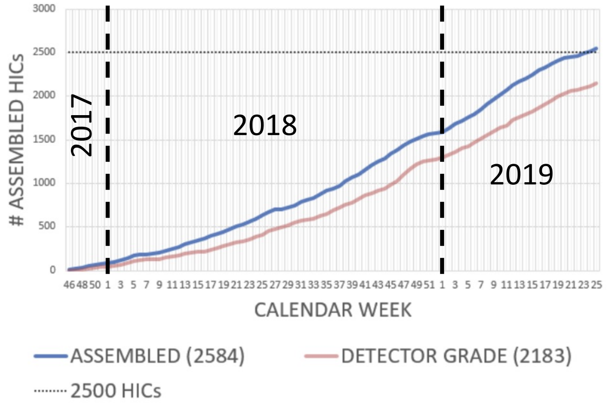
- Institutes: CERN
- 140 staves assembled
- Yield 73%
- Enough for 2 fully working copies of the IB



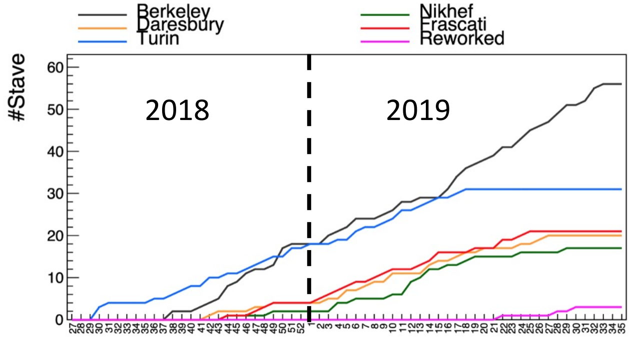
Outer barrel HICs and staves

Production completed

- HIC institutes: Bari (IT), Liverpool (UK), Pusan (KR), Strasbourg (FR), Wuhan (CN)
- FPCs: Trieste (IT)
- >2500 HICs assembled
- Yield ~85%



- Stave institutes: Berkeley (US), Daresbury (UK), Frascati (IT), Nikhef (NL), Turin (IT)
- 148 staves assembled
- Yield > 90%
- Rework yield ~50%



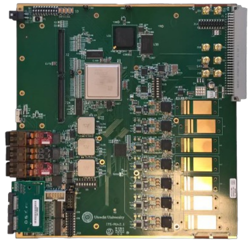
Component Production Status

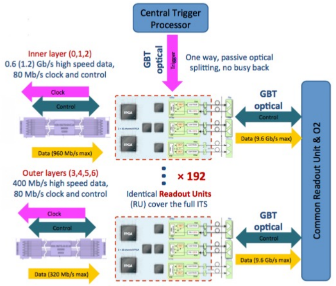
ALICE

Readout electronics

Production completed

- Institutes: Austin (US), Bergen (NO), CERN, Nikhef (NL), Padova (IT)
- 192 FPGA based RUs, operating in a mild radiation environment (<10 krad, 10^{11} 1 MeV/n_{eq})

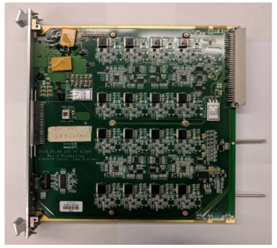


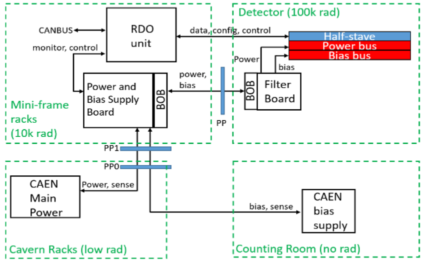


Power system

Production completed

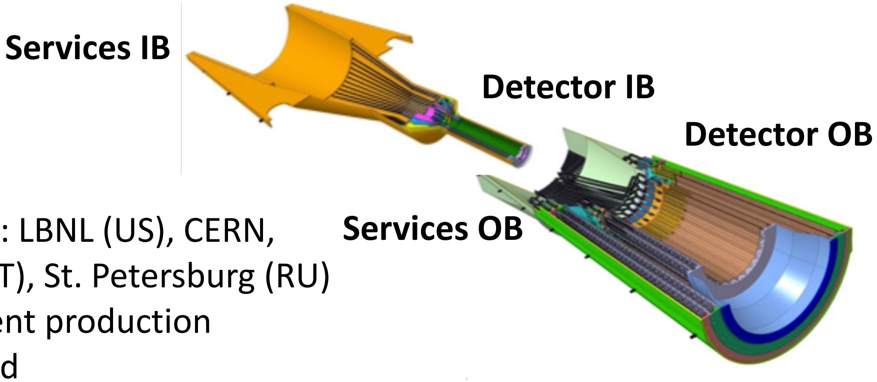
- Institutes: LBNL (US), Bari (IT)
- CAEN powering modules available and in use in commissioning setup





Support structures

Production completed



- Institutes: LBNL (US), CERN, Padova (IT), St. Petersburg (RU)
- Component production completed
- Insertion dry test performed